IGN OF A PLANT TO PRODUCE 10 TONNES/HOUR OF LIME FROM LIMESTONE

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NOVEMBER, 2005

DESIGN OF A PLANT TO PRODUCE 10 TONNES/HOUR OF LIME FROM LIMESTONE

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A DESIGN PROJECT SUBMITTED TO THE
DEPARTMENT OF CHEMICAL ENGINEERING, SCHOOL
OF ENGINEERING AND ENGINEERING TECHNOLOGY,
FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGER
STATE, NIGERIA

IN PARTIAL FULFILMENT OF THE REQUIREMENT
FOR THE AWARD OF BACHELOR OF ENGINEERING
(B.ENG.) DEGREE IN CHEMICAL ENGINEERING.

NOVEMBER, 2005

DECLARATION

Wodung Stephen (99/8411EH), hereby declare that this design project, “Design a Plant to Produce 10 Tonnes/Hour of Lime from Limestone”, carried out under e supervision of Prof. Odigure, J. O. and presented in partial fulfilment of the quirement for the award of Bachelor of Engineering (B.Eng.) degree in Chemical gineering has not been presented for any degree elsewhere, to the best of my owledge.

18/12/05

Wodung Stephen

Date

CERTIFICATION

his is to certify that this design project tiled “Design of a Plant to Produce 10 nnes/Hour of Lime from Limestone” was carried out by Wodung Stephen 9/8411EH) and submitted to the Department of Chemical Engineering, School of ngineering and Engineering Technology, Federal University of Technology, inna, Niger State, in partial fulfilment of the requirement for award of Bachelor Engineering (B.Eng.) degree in Chemical Enginnering.

________________________ ________________

Prof. Odigure, J. O. Date

(Project Supervisor)

________________________ ________________

Dr. F. Aberuagba Date

(Head of Department)

________________________ ________________

External Examiner Date

DEDICATION

is design project is dedicated to the entire Wodung family and to my younger others and sisters, for by the grace of God will grow to challenge this project.

ACKNOWLEDGEMENT

l praise and gratitude to God Almighty creator of heavens and earth for giving e the strength, courage, patience and perseverance, the strong will and termination to complete my course successfully,

I must register my sincere appreciation to my parents Engr. S.L Hassan and rs. A.K. Hassan for their love, care and support despite all disappointments. May od in his infinite mercy reward them abundantly in Jesus name. Amen.

I must also place in record my profound gratitude to my able supervisor of. Odigure, J.O. whose comments corrections, and criticism gave this project a nse of direction. Worthy of mention also are some of my brothers Mr. Gregory odung, Dr. Fidelis Wodung, Ibro and Philip. To my sisters Miss Angela odung, Barrister Martina Wodung, Veronica Bature, Dinah, Abi, Bebo and amari. May God bless you all.

Worthy of mention also are some of my friends Tabat, Huzzy,Lash, John i, Lolo, JD, Lomi, Bafot as well as my entire course mates. In fact it was a onderful time.

This project would have been incomplete if I fail to acknowledge the kind sistance rendered to me by the entire staff of Chemical Engineering Department, ost especially Engr. A. Jimoh and all others that are too numberous to mention.

ABSTRACT

This project was carried out to design of a plant to produce 10 tonnes/hour of lime from limestone. Even though the product can be produced using another material lime the chalk and phosphate gypsum, the production using limestone was selected because of the availability of the material (limestone). The chemical equation of the reaction involved in the production of the lime from the limestone is given as

$$CaCO_3 \rightleftharpoons CaO + CO_2 \quad \Delta H_{1200-1300^oC} = +4GJ/t \text{ of lime}$$

The production for the production of the required capacity which was 10 tonnes/hour of lime involved passing 18143.69 kg/hr into the furnace. The various units including the furnace used for the production of the lime from limestone were designed. The economic analysis of the plant showed that the total capital investment of the plant was ₦844102901.47. The plant was found to be economically viable with the rate of return of 42.86% and a pay back period of 2.33 years.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Lime

1.1.1 Lime, what is it?

Lime is caustic solid substance, white when pure, obtained by calcining chalk and other forms of calcium carbonate. Pure lime, also called quicklime, burnt lime, and caustic lime, is composed of calcium oxide (CaO) but commercial preparations usually contain impurities, such as the oxides of aluminium, iron, silicon, and magnesium. When treated with water, lime liberates large amounts of heat and forms calcium hydroxide, sold commercially as a white powder called slaked lime or hydrated lime. Lime is used in the preparation of cement and mortar and as a neutralizer of acid soils in agriculture. It is also used in the manufacture of paper, glass, and whitewash, in leather tanning, sugar refining, and as a water-softening agent. (Encarta, 2004)

1.1.2 Historical background of lime

In 1816, Thomas Drummond invented limelight, and in 1825 its first use was during a survey of Ireland. Drummond's early limelight was based on a torch that burned hydrogen and oxygen, which had been developed by Robert Hare (1781-1858), an American chemist. Although limelight was considered for lighthouse applications, the cost of production was too high. In 1837, limelight found its niche in the theater, where it was used not only to spotlight actors but also to create realistic special effects such as moonlight on a river or clouds moving through the sky. The light was produced by pointing a hot torch at a solid block of lime (calcium oxide). When heated, the lime gave off a bright, soft white light that was easy to focus on a small area by using a mirror as a reflector. However, limelight had a major disadvantage; it required constant attention by a stagehand to keep turning the block of lime and tending the gas torch. In the late 1800s, limelight began to be replaced by electric arc spotlights. However, its name has lived on; we still speak today of "basking in the limelight" of popularity or attention. (www.bookrags.com/sciences/chemistry/lime-woc.html)

1.1.3 Properties of lime

General	
Name	Calcium oxide
Chemical formula	CaO
Appearance	White solid
Physical	
Formula weight	56.1 amu
Melting point	2572 K (2927 °C)
Boiling point	2850 K (3500 °C)
Density	3.3×103 kg/m^3
Crystal structure	Face-Centered Cubic
Solubility	hydrolysed
Thermochemistry	
$\Delta_f H^0$gas	43.93 kJ/mol
$\Delta_f H^0$liquid	−557.33 kJ/mol
$\Delta_f H^0$solid	−635.09 kJ/mol
S^0gas, 1 bar	219.71 J/mol·K
S_0liquid, 1 bar	62.31 J/mol·K
S_0solid	38.19 J/mol·K

1.1.4 Uses of Lime

Mortar (masonry) is mixture of lime or cement with sand and water, used as a binding material for bricks and stone and as a plaster. Lime mortar consists of sand, water, and slaked lime ($Ca(OH)_2$), a white solid produced when lime reacts with water. Usually one part by volume of slaked lime is used for every three or four parts by volume of sand; enough water is added to make a paste. When exposed to the atmosphere the paste hardens as the result of absorption of carbon dioxide. It does not harden under water and is not as strong as cement mortar. The best type of cement mortar is a mixture of portland cement, sand, water, and a small amount of lime. (Encarta, 2004)

It is also used in water and sewage treatment to reduce acidity, to soften, as a flocculant and to remove phosphates and other impurities; in paper making to dissolve lignin, as a coagulant and in bleaching; in agriculture to improve acid soils; and in pollution control - in gas scrubbers to desulfurize waste gases and to treat many liquid effluents. It is a refactory and a dehydrating agent and is used to purify citric acid, glucose, dyes and as a CO_2 absorber. It is also used in pottery, concrete, paints and the food industry. (http://en.wikipedia.org/wiki/Calcium_oxide)

1.2 Limestone

Limestone ($CaCO_3$) is a chemical compound which is commonly used as an antacid, and is the active ingredient in agricultural lime. It is a common substance found as rock in all parts of the world and is the main component of seashells and the shell of snails. (http://en.wikipedia.org/wiki/Calcium_carbonate)

Limestone is a common sedimentary rock composed primarily of the mineral calcite ($CaCO_3$). Limestone constitutes approximately 10 percent of the sedimentary rocks exposed on the earth's surface. It forms either by direct crystallization from water (usually seawater) or by accumulation of shell and shell fragments. In the first case, it carries a record of the chemical composition of seawater and it provides evidence of how that composition has changed with time. In the second case, limestone provides a record of the evolution of many important fossils. Limestone usually forms in shallow water less than 20 m (70 ft) deep and thus also provides important geological information on the variation in sea level in the past. Limestone rocks are frequently riddled with caves. Limestone is an important building stone and is used to make cement and concrete. (Encarta, 2004)

Limestone is a sedimentary rock composed of the mineral calcite. It is sometimes formed with the aid of marine organisms, such as shellfish and coral, which acquire calcium carbonate for their protective shells. When the organisms die, these shells form calcite deposits that harden into limestone over millions of years.

When a drop of dilute hydrochloric acid is placed on a piece of limestone, the acid reacts with the calcite and forms bubbles of carbon dioxide. This "fizz" reaction is so characteristic of limestone than many geologists carry a small bottle of dilute hydrochloric acid into the field for a rapid and easy identification of limestone. (Encarta, 2004)

1.2.1 Composition and origin of limestone

The principal component of limestone is the mineral calcite, but limestone frequently also contains the minerals dolomite ($CaMg(CO_3)_2$) and aragonite ($CaCO_3$). Pure calcite, dolomite, and aragonite are clear or white. However, with impurities, they can take on a variety of colours. Consequently, limestone is commonly light coloured; usually it is tan or grey. However, limestone has been found in almost every colour. The colour of limestone is due to impurities such as sand, clay, iron oxides and hydroxides, and organic materials.

All limestone forms from the precipitation of calcium carbonate from water. Calcium carbonate leaves solutions in many ways and each way produces a different kind of limestone. All the different ways can be classified into two major groups: either with or without the aid of a living organism. (Encarta, 2004)

Most limestone is formed with the help of living organisms. Many marine organisms extract calcium carbonate from seawater to make shells or bones. Mussels, clams, oysters, and corals do this. So too do microscopic organisms such as foraminifera. When the organisms die their shells and bones settle to the seafloor and accumulate there. Wave action may break the shells and bones into smaller fragments, forming a carbonate sand or mud. Over millions of years, these sediments of shells, sand, and mud may harden into limestone. Coquina is a type of limestone containing large fragments of shell and coral. Chalk is a type of limestone formed of shells of microscopic animals. (Encarta, 2004)

1.2.2 History of Limestone

In the highly developed cultures of Mesopotamia and Egypt, limestone was used particularly in a religious context. Egypt had enormous sources of very differing types of stone. Limestone was just one of a range of stones that were quarried and used for carving statues of the deities and the pharaohs, for obelisks, reliefs and sarcophaguses**. Quarrying and processing techniques, in particular the administrative and logistics were highly developed in Egypt. (www.wzu.uni-augsburg.de/English/Projects/History_of_Limestone.html)

The quarrying companies and companies producing statues employed several thousand people. In the Egyptian culture, stone was the symbol of permanency/eternity and power and this meant that stone had an all-important function to play in society. This importance is very clear to see when we consider the steady increase of the importance of the choice of stone used. (www.wzu.uni-augsburg.de/English/Projects/History_of_Limestone.html)

Many pharaohs showed their power by having quarries opened up especially for them and having stone quarried, which was for their personal use only. The fight for power and status symbols increased in all cultures corresponding to the continual increase of contact with other peoples, through trade and wars and the jealousies arising from these meetings.

(www.wzu.uni-augsburg.de/English/Projects/History_of_Limestone.html)

The natural colouring of marble and its characteristic of light transparency particularly after it has undergone complicated treatment and polishing, let it appear to be like human skin. This material enabled the sculpturers to achieve an actual imitation of nature, a realistic effect. (www.wzu.uni-augsburg.de/English/Projects/History_of_Limestone.html)

1.2.3 Properties of limestone

1.2.3.1 Physical properties of limestone

General	
Molecular formula	$CaCO_3$
Molar mass	100.09 g/mol
Appearance	white solid
Properties	
Density and phase	2.8 g/cm^3, solid
Solubility in water	Insoluble
Melting point	825 °C decomp.

1.2.3.2 Chemical properties of limestone

Calcium carbonate shares the typical properties of other carbonates. Notably:

1. it reacts with strong acids, releasing carbon dioxide.

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$$

1. it releases carbon dioxide on heating (to above 825 °C in the case of $CaCO_3$), to form calcium oxide.

$$CaCO_3 \rightarrow CaO + CO_2$$

Calcium carbonate will react with water that is saturated with carbon dioxide to form the soluble calcium bicarbonate.

$$CaCO_3 + CO_2 + H_2O \; \square \; Ca(HCO_3)_2$$

This reaction is important in the erosion of carbonate rocks, forming caverns, and leads to hard water in many regions.

1.2.4 Occurrence of limestone

Calcium carbonate is found naturally as the following minerals and rocks: (http://en.wikipedia.org/wiki/Calcium_carbonate)

- Aragonite
- Calcite
- Chalk
- Limestone
- Marble
- Travertine

1.2.5 Weathering and metamorphism of limestone

Limestone is easily weathered and eroded. Water trickling through large limestone deposits often erodes extensive underground drainage systems of sinkholes and caves. The land surface above large limestone deposits is often irregular, marked with potholes (formed when the roofs of shallow caves collapse), sinkholes, and few streams, most of which are short in length and end in a sinkhole. The irregular surface is known as karst topography, named after a limestone plateau in the Dinaric Alps of northwest Slovenia and northeast Italy. Within the caverns, secondary precipitation of calcite by percolating waters produces stalactites and stalagmites, and spectacular underground 'scenery' can result. (Encarta, 2004)

When limestone undergoes metamorphism, it turns into marble. If the limestone contains other materials such as sand and clay, the calcite will react with them to produce minerals such as tremolite, epidote, diopside, and grossular garnet. (Encarta, 2004)

1.2.6 Uses of limestone

The main use of calcium carbonate is in the construction industry, either as a building material in its own right (e.g. marble) or as an ingredient of cement.

Limestone is a commonly occurring rock, which can be used not only for building but also for making manyother useful materials including lime, cement and glass. Limestone, which is mainly calcium carbonate, canbe quarried and used as a building material. Powdered limestone can be used to neutralise acidity in lakesand soils. When limestone is heated in a kiln quicklime (calcium oxide) is produced. Quicklime reacts withwater to produce slaked lime (calcium hydroxide) which is used to reduce soil acidity. Roasting powdered limestone with powdered clay in a rotary kiln produces cement. When cement is mixed with water, sand and crushed rock, a slow chemical reaction produces a hard, stone-like building material called concrete.Heating a mixture of limestone, sand and soda (sodium carbonate) makes glass.

Calcium carbonate is widely used in the pharmaceutical industry, either as an antacid or as a base material for tablets of other pharmaceuticals. (http://en.wikipedia.org/wiki/Calcium_carbonate)

Calcium carbonate is known as whiting in ceramics/glazing applications, where it is used as a common ingredient for many glazes in its white powdered form. When a glaze containing this material is fired in a kiln, the whiting acts as a flux material in the glaze. (http://en.wikipedia.org/wiki/Calcium_carbonate)

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Description of various processing technologies

The various technologies available for the production of lime include production using:

1. industrial by-product containing phosphate commonly referred to as phosphate gypsum;
2. soft lime commonly called chalk;
3. limestone.

2.2 Detail Description of Selected Technology

Lime has always been a cheap commodity because limestone deposits are readily available in so many areas of Nigeria. It is produced from limestone near centres of consumption so that freight costs are low. The carbonates of calcium and magnesium are obtained from deposits of limestone, marble, chalk, dolomite or oyster shells. For chemical usage, a rather pure limestone is preferred as a starting material because of the high calcium lime that results. (Austin, 1984)

Quarries are chosen which furnish a rock that contains as impurities low percentages of silica, clay, or iron. The lumps sometimes found in "overburned" or "deadburned" lime result from changes in the calcium oxide itself, as well as from certain impurities acted upon by excess heat, recognized as masses of relatively inert, semivitrified material. On the other hand, it often happens that rather pure limestone is calcined insufficiently, and lumps of calcium carbonate are left in the lime. The lime is called "underburned" lime. (Austin, 1984)

The reactions involved is given as

$$CaCO_{3(c)} \rightleftharpoons CaO_{(c)} + CO_{2(g)}$$

Below 650°C, the equilibrium decomposition pressure of CO_2 is quite small. Between 650 and 900°C, the decomposition pressure increases rapidly and reaches 101kPa at about 900°C. In most operating furnaces, the partial pressure of CO_2 in the gases in direct contact with the outside of the lumps is less than 101kPa; therefore the initial decomposition may take place at temperatures somewhat less than 900°C. The decomposition temperature at the centre of the lump is probably well above 900°C, since there the partial pressure of the CO_2 not only is equal to or near the total pressure, but also must be high enough to cause the gas to move out of the lump, where it can pass into the gas stream. The total heat required for calcining per ton of lime produced may be divided into two parts: sensible heat to raise the rock to decomposition temperature and latent heat of dissociation. Theoretical heat requirements per metric ton of lime produced, if the rock is heated only to a calcining temperature of 900°C, are approximately 1.4GJ for sensible heat and 2.7GJ for latent heat. Actual calcining operations, because of practical considerations, e.g. lump size and time, require that the rock be heated to between 1200 and 1300°C, thereby increasing sensible-heat requirements by about 370kJ.

The sequence of steps connected with the manufacturing of lime in the furnace are outlined thus;

- Blasting down of limestone from a quarry face or occasionally from underground veins.
- Transportation from the quarry to mills, generally by an industrial rail road.
- Crushing and sizing of the stone in jaw and gyratory crushers.

- Screening to remove various sizes (e.g. 10- to 20-cm stone implies that all pieces passes a 10-cm screen and retained on an 20-cm screen have been separated out.
- Carting of large stones to top of vertical kilns.
- Conveying of small rocks to the furnace.
- Burning of limestone according to size, in furnace to give lump lime.
- Packaging of the finished lime in barrels (80 or 120kg) or sheet-iron drums or convey it to hydrator. (Austin, 1984)

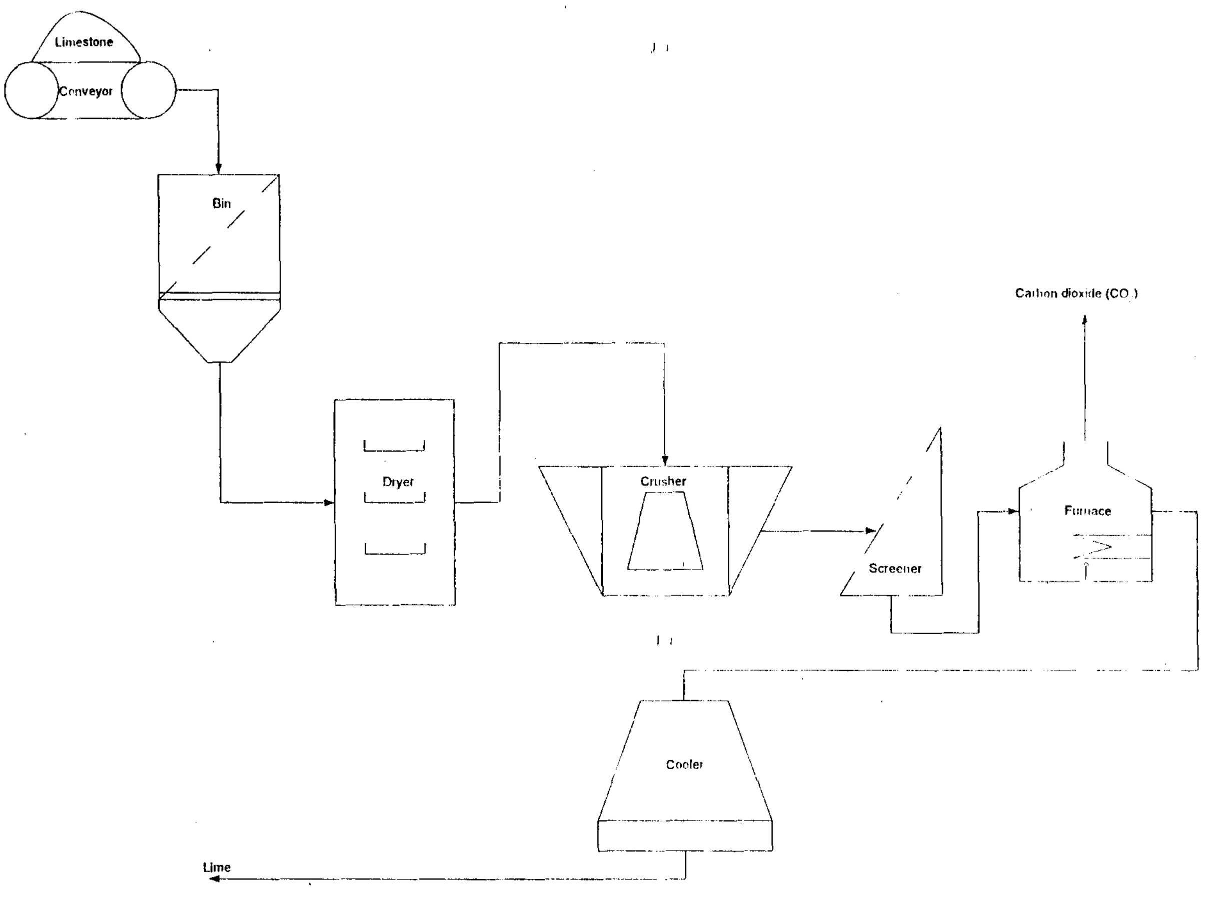


Fig. 2.1: Flow sheet for production of lime using limestone

2.3 Justification of the Selected Technology

The reason for choosing processing technology using limestone for the production of lime is that limestone is available abundantly in many parts of the country. For example, limestone deposits in abundant quantities are found in states like Edo, Ogun, Benue and Sokoto States.

CHAPTER THREE

3.0 MATERIAL BALANCES

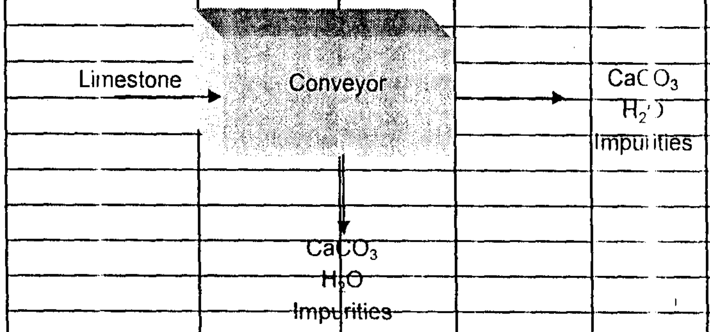
Basis: 100.00 kg/hr of limestone

Composition of the raw material (limestone)

Components	mass%
$CaCO_3$	95.00
H_2O	2.30
Impurities	2.70
Total	100.00

Unit 1: Conveyor

Operation: Transportation of limestone from field to bin

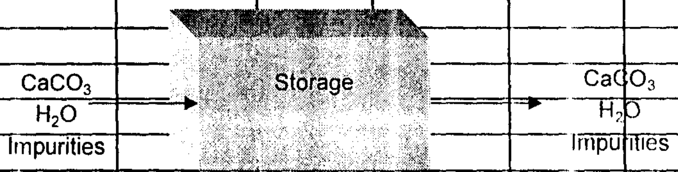


Assumption: No material loss

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	95.00	95.00	0.00	0.00	0.95	95.00	94.05	95.00
H_2O	2.30	2.30	0.00	0.00	0.02	2.30	2.28	2.30
Impurities	2.70	2.70	0.00	0.00	0.03	2.70	2.67	2.70
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	0.00	0.00	1.00	100.00	99.00	100.00

Unit 2: Bin

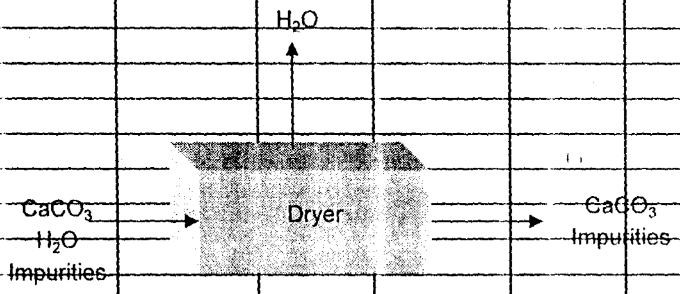
Operation: Storage of limestone



	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	94.05	95.00	0.00	0.00	0.00	0.00	94.05	95.00
H_2O	2.28	2.30	0.00	0.00	0.00	0.00	2.28	2.30
Impurities	2.67	2.70	0.00	0.00	0.00	0.00	2.67	2.70
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.00	100.00	0.00	0.00	0.00	0.00	99.00	100.00

Unit 3: Dryer

Operation: Drying (Removal of moisture)

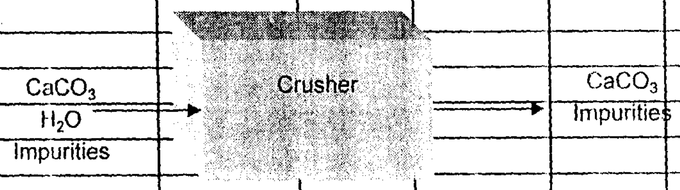


Assumption: Total removal of moisture

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	94.05	95.00	0.00	0.00	0.00	0.00	94.05	97.24
H_2O	2.28	2.30	0.00	0.00	2.28	100.00	0.00	0.00
Impurities	2.67	2.70	0.00	0.00	0.00	0.00	2.67	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.00	100.00	0.00	0.00	2.28	100.00	96.72	100.00

Unit 4: Crusher

Operation: Size reduction

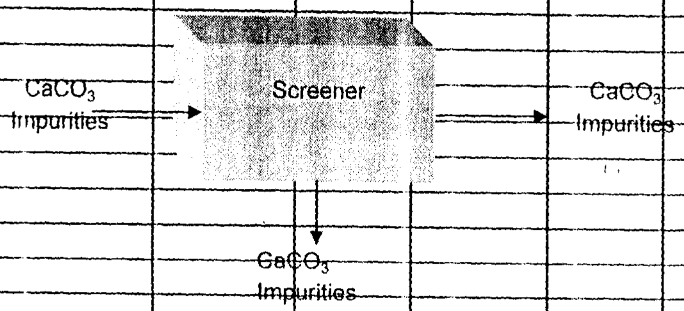


Assumption: 1.5% material loss

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	94.05	97.24	0.00	0.00	1.41	97.24	92.64	97.24
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	2.67	2.76	0.00	0.00	0.04	2.76	2.63	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	96.72	100.00	0.00	0.00	1.45	100.00	95.27	100.00

. Screener

Operation: Classification of particles into different sizes



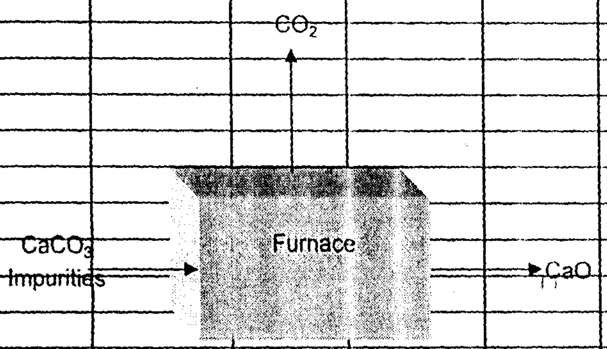
Assumption: 95% of material recovered

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	92.64	97.24	0.00	0.00	4.63	97.24	88.01	97.24
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	2.63	2.76	0.00	0.00	0.13	2.76	2.50	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	95.27	100.00	0.00	0.00	4.76	100.00	90.51	100.00

Unit 6: Furnace

Process: Calcination

Calcination 1: $CaCO_3$ + Heat $\longrightarrow$ CaO + CO_2

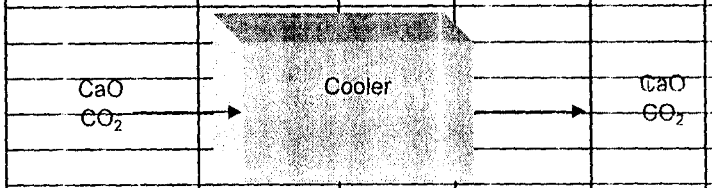


NB: The material balances around the furance is based on the chemical reaction shown above

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	88.01	97.24	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	2.50	2.76	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00	49.28	100.00
CO_2	0.00	0.00	0.00	0.00	38.72	100.00	0.00	0.00
Total	90.51	100.00	0.00	0.00	38.72	100.00	49.28	100.00

Unit 7: Cooler

Operation: Lowering the temperature of the product



	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	49.28	100.00	0.00	0.00	0.00	0.00	49.28	100.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	49.28	100.00	0.00	0.00	0.00	0.00	49.28	100.00

Calculation of scale factor

Molecular weights of the components

Component	kg/kgmol
$CaCO_3$	100.00
H_2O	18.00
Impurities	60.00
CaO	56.00
CO_2	44.00

Conversion facto 1.00 ton/hr = 1016.05 kg/hr

Lime production rate = 10.00 tons/hr which is equal to 10160.47 kg/hr

The total mass of the components indicates the mass of lime produced from the basis.

So, lime produced from the basis (100kg/hr) = 49.28 kg/hr

In other words, the final output = 49.28 kg/day

The scale-up factor = 206.16

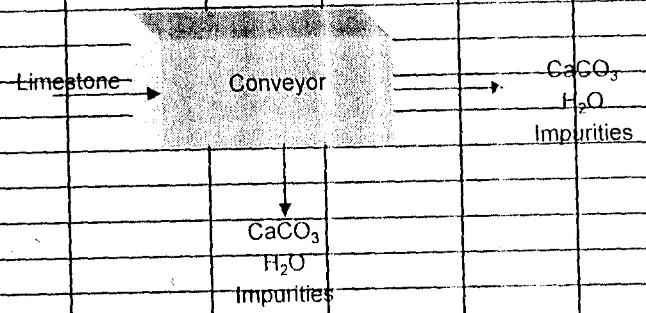
The scale up factor will be used to scale up the masses of the different components in each unit.

SCALED MATERIAL BALANCES (Scaling up to furnace productivity of 10T/hr)

Unit 1: Conveyor

Operation: Conveyance of the raw material from the quarry to the storage tank

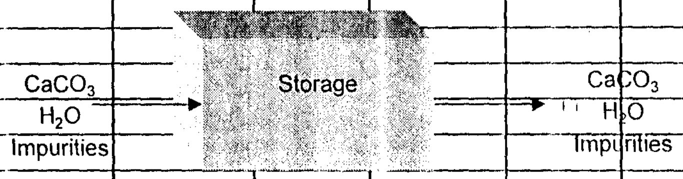
Assumption: 100% material recovery



	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass. kg/hr	mass%
$CaCO_3$	19585.32	95.00	0.00	0.00	195.85	95.00	19389.47	95.00
H_2O	474.17	2.30	0.00	0.00	4.74	2.30	469.43	2.30
Impurities	556.64	2.70	0.00	0.00	5.57	2.70	551.07	2.70
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	20616.13	100.00	0.00	0.00	206.16	100.00	20409.97	100.00

Unit 2: Bin

Operation: Storage of the raw material

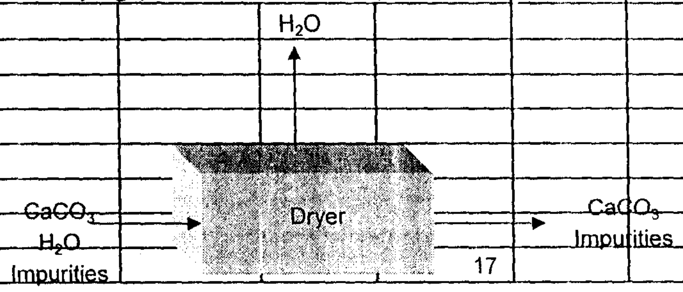


Assumption: No material is lost in the storage

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	19389.47	95.00	0.00	0.00	0.00	0.00	19389.47	95.00
H_2O	469.43	2.30	0.00	0.00	0.00	0.00	469.43	2.30
Impurities	551.07	2.70	0.00	0.00	0.00	0.00	551.07	2.70
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	20409.97	100.00	0.00	0.00	0.00	0.00	20409.97	100.00

Unit 3: Dryer

Operation: Drying (Removal of moisture)



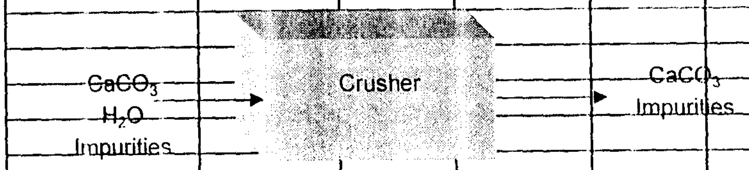
Impurities								

Assumption: All the water in the raw material was removed by the dryer

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	19389.47	95.00	0.00	0.00	0.00	0.00	19389.47	97.24
H_2O	469.43	2.30	0.00	0.00	469.43	100.00	0.00	0.00
Impurities	551.07	2.70	0.00	0.00	0.00	0.00	551.07	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	20409.97	100.00	0.00	0.00	469.43	100.00	19940.54	100.00

Unit 4: Crusher

Operation: Size reduction (crushing)

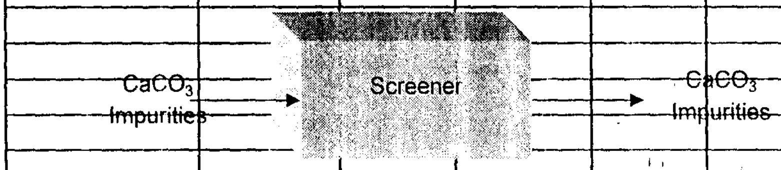


Assumption: 1.7% material loss

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	19389.47	97.24	0.00	0.00	290.84	97.24	19098.63	97.24
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	551.07	2.76	0.00	0.00	8.27	2.76	542.80	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	19940.54	100.00	0.00	0.00	299.11	100.00	19641.43	100.00

Unit 5: Screener

Operation: Classification of particles into different sizes



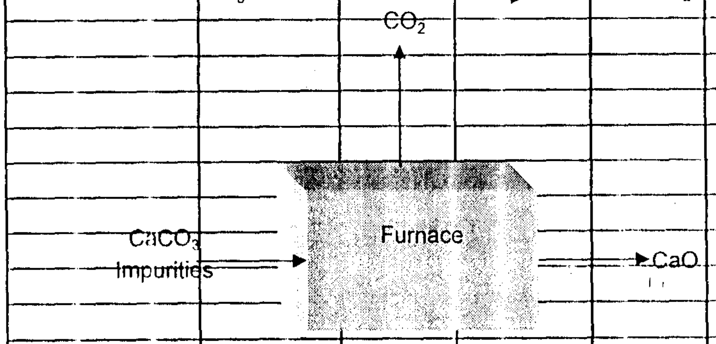
Assumption: 95% of the material fall within the specified sizes of 0.64 - 3.4cm

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	19098.63	97.24	0.00	0.00	954.93	97.24	18143.69	97.24
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	542.80	2.76	0.00	0.00	27.14	2.76	515.66	2.76
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	19641.43	100.00	0.00	0.00	982.07	100.00	18659.36	100.00

Unit 6: Furnace

Process: Calcination

Calcination 1: $CaCO_3$ + Heat $\rightarrow$ CaO + CO_2

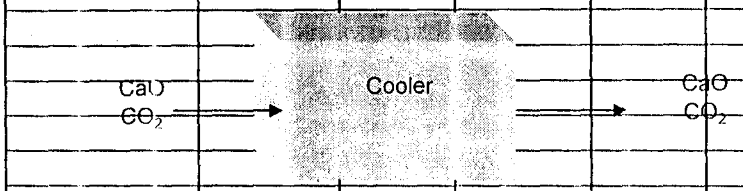


Note: The calcination equation above will be used to determine the material generated

	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	18143.69	97.24	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	515.66	2.76	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00	10160.47	100.00
CO_2	0.00	0.00	0.00	0.00	7983.23	100.00	0.00	0.00
Total	18659.36	100.00	0.00	0.00	7983.23	100.00	10160.47	100.00

Unit 7: Cooler

Operation: Lowering the temperature of the product (lime)



	IN				OUT			
	Input		Added		Loss		Output	
Components	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%	mass, kg/hr	mass%
$CaCO_3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	10160.47	100.00	0.00	0.00	0.00	0.00	10160.47	100.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	10160.47	100.00	0.00	0.00	0.00	0.00	10160.47	100.00

Final product (Lime):

Components	mass, kg/hr	mass%
$CaCO_3$	0.00	0.00
H_2O	0.00	0.00
Impurities	0.00	0.00
CaO	10160.47	100.00
CO_2	0.00	0.00
Total	10160.47	100.00

CHAPTER FOUR

4.0 ENERGY BALANCES

$$\mathrm{MW} := \begin{pmatrix} 100.09 \\ 18.016 \\ 60.00 \\ 56.08 \\ 44.01 \end{pmatrix} \cdot \frac{\mathrm{kg}}{\mathrm{kmol}} \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Heat capacity coefficients:

$$\mathrm{cm} := \begin{pmatrix} 82.34 & 4.975 \cdot 10^{-2} & -12.87 \cdot 10^{10} \cdot 10^{-5} & 0 \\ 18.2964 & 47.212 \cdot 10^{-2} & -133.88 \cdot 10^{-5} & 1314.2 \cdot 10^{-9} \\ 15.2 & 2.68 \cdot 10^{-2} & 0 & 0 \\ 41.84 & 2.03 \cdot 10^{-2} & -4.52 \cdot 10^{10} \cdot 10^{-5} & 0 \\ 36.11 & 4.233 \cdot 10^{-2} & -2.887 \cdot 10^{-5} & 7.464 \cdot 10^{-9} \end{pmatrix} \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

(Himmelblau, 1996)

$$a := \overrightarrow{\frac{\mathrm{cm}^{\langle 1 \rangle}}{\mathrm{MW} \cdot \frac{\mathrm{kmol}}{\mathrm{kg}}}} \qquad b := \overrightarrow{\frac{\mathrm{cm}^{\langle 2 \rangle}}{\mathrm{MW} \cdot \frac{\mathrm{kmol}}{\mathrm{kg}}}} \qquad c := \overrightarrow{\frac{\mathrm{cm}^{\langle 3 \rangle}}{\mathrm{MW} \cdot \frac{\mathrm{kmol}}{\mathrm{kg}}}} \qquad d := \overrightarrow{\frac{\mathrm{cm}^{\langle 4 \rangle}}{\mathrm{MW} \cdot \frac{\mathrm{kmol}}{\mathrm{kg}}}}$$

$$\mathrm{coeff} := \mathrm{augment}(a, b, c, d)$$

$$\mathrm{coeff} = \begin{pmatrix} 0.823 & 0 & -12858.427 & 0 \\ 1.016 & 0.026 & -7.431 \times 10^{-5} & 7.295 \times 10^{-8} \\ 0.253 & 0 & 0 & 0 \\ 0.746 & 0 & -8059.914 & 0 \\ 0.82 & 0.001 & -6.56 \times 10^{-7} & 1.696 \times 10^{-10} \end{pmatrix}$$

$$a := a \cdot \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}} \qquad b := b \cdot \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^2} \qquad c := c \cdot \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^3} \qquad d := d \cdot \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^4}$$

$$a = \begin{pmatrix} 0.823 \\ 1.016 \\ 0.253 \\ 0.746 \\ 0.82 \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}} \qquad b = \begin{pmatrix} 0 \\ 0.026 \\ 0 \\ 0 \\ 0.001 \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^2} \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

$$c = \begin{pmatrix} -12858.427 \\ -7.431 \times 10^{-5} \\ 0 \\ -8059.914 \\ -6.56 \times 10^{-7} \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^3} \qquad d = \begin{pmatrix} 0 \\ 7.295 \times 10^{-8} \\ 0 \\ 0 \\ 1.696 \times 10^{-10} \end{pmatrix} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^4} \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Heat of formation:

$$H_f := \begin{pmatrix}-1206.9\\-285.84\\-851.0\\-635.6\\-393.51\end{pmatrix}\cdot 10^3\cdot\frac{kJ}{kmol} \qquad \begin{pmatrix}CaCO_3\\H_2O\\Impurities\\CaO\\CO_2\end{pmatrix}$$

(Himmelblau, 1996)

$$H_f := \frac{\overrightarrow{H_f}}{MW}$$

$$H_f = \begin{pmatrix}-12058.148\\-15865.897\\-14183.333\\-11333.809\\-8941.377\end{pmatrix}\frac{kJ}{kg} \qquad \begin{pmatrix}CaCO_3\\H_2O\\Impurities\\CaO\\CO_2\end{pmatrix}$$

4.3.1 ENERGY BALANCES ACROSS THE BIN

The energy balances of the bin will be calculated using

$$\Delta H = \dot{m}\cdot C_p\cdot\Delta T$$

where

m = "mass"

C_p = "heat capacity" which is given as $C_p = a + b\cdot T + c\cdot T^2 + d\cdot T^3$

ΔT = "change in temperature" which is given as $\Delta T = T_{in} - T_{ref}$

ENERGY INPUT ACROSS THE BIN

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix}19389.47\\469.43\\551.07\\0.00\\0.00\end{pmatrix}\cdot\frac{kg}{hr} \quad \text{and} \quad T_{in} := \left[\begin{pmatrix}10\\10\\10\\10\\10\end{pmatrix} + 273\right]\cdot K \qquad \begin{pmatrix}CaCO_3\\H_2O\\Impurities\\CaO\\CO_2\end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273)\cdot K$

Inlet temperature: $T_{in_1} = 283\ K$

$\Delta T_1 := T_{in_1} - T_{ref}$

$\Delta T_1 = -10\,K$

$a_1 = 0.823\,\frac{kJ}{kg \cdot K}$

$b_1 = 0\,\frac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427\,\frac{kJ}{kg \cdot K^3}$

$d_1 = 0\,\frac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + d_1 \cdot \left(T_{in_1}\right)^3\right]$

$C_{p1} = -1.03 \times 10^{9}\,\frac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = 1.997 \times 10^{14}\,\frac{kJ}{hr}$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 283\,K$

$\Delta T_2 := T_{in_2} - T_{ref}$

$\Delta T_2 = -10\,K$

$a_2 = 1.016\,\frac{kJ}{kg \cdot K}$

$b_2 = 0.026\,\frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5}\,\frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8}\,\frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3\right]$

$C_{p2} = 4.134\,\frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$

$\Delta H_{H2O} = -19404.061\,\frac{kJ}{hr}$

Energy of impurities input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 283\,K$

$\Delta T_3 := T_{in_3} - T_{ref}$ $\Delta T_3 = -10\,K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3 \right]$ $C_{p3} = 0.38 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = -2092.633 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 283\,K$

$\Delta T_4 := T_{in_4} - T_{ref}$ $\Delta T_4 = -10\,K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right] \qquad C_{p4} = -6.455 \times 10^{8}\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \qquad \Delta H_{CaO} = 0\,\frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} = 283\,K$

$$\Delta T_5 := T_{in_5} - T_{ref} \qquad \Delta T_5 = -10\,K$$

$$a_5 = 0.82\,\frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001\,\frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7}\,\frac{kJ}{kg \cdot K^3}$$

$$d_5 = 1.696 \times 10^{-10}\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right] \qquad C_{p5} = 1.044\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \qquad \Delta H_{CO2} = 0\,\frac{kJ}{hr}$$

Total energy in: $\Delta H_{in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{in} = 1.997 \times 10^{14}\,\frac{kJ}{hr}$$

ENERGY OUTPUT ACROSS THE BIN

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 19389.47 \\ 469.43 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{out} := \left[\begin{pmatrix} 13 \\ 13 \\ 13 \\ 13 \\ 13 \end{pmatrix} + 273\right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_1} = 286\,K$

$\Delta T_1 := T_{out_1} - T_{ref}$

$\Delta T_1 = -7\,K$

$a_1 = 0.823 \frac{kJ}{kg \cdot K}$

$b_1 = 0 \frac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$

$d_1 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right]$

$C_{p1} = -1.052 \times 10^{9} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = 1.428 \times 10^{14} \frac{kJ}{hr}$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 286\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$

$\Delta T_2 = -7\,K$

$a_2 = 1.016 \frac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3\right]$ $\quad C_{p2} = 4.138\,\frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$ $\quad \Delta H_{H2O} = -13598.963\,\frac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 286\,K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\quad \Delta T_3 = -7\,K$

$a_3 = 0.253\,\frac{kJ}{kg \cdot K}$

$b_3 = 0\,\frac{kJ}{kg \cdot K^2}$

$c_3 = 0\,\frac{kJ}{kg \cdot K^3}$

$d_3 = 0\,\frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3\right]$ $\quad C_{p3} = 0.381\,\frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$ $\quad \Delta H_{Impurities} = -1470.012\,\frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 286\,K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\quad \Delta T_4 = -7\,K$

$a_4 = 0.746\,\frac{kJ}{kg \cdot K}$

$b_4 = 0\,\frac{kJ}{kg \cdot K^2}$

$$c_4 = -8059.914\,\frac{kJ}{kg \cdot K^3}$$

$$d_4 = 0\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right] \qquad C_{p4} = -6.593 \times 10^8\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$\Delta H_{CaO} = 0\,\frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 286\,K$

$$\Delta T_5 := T_{out_5} - T_{ref} \qquad \Delta T_5 = -7\,K$$

$$a_5 = 0.82\,\frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001\,\frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7}\,K\,\frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10}\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right] \qquad C_{p5} = 1.046\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$\Delta H_{CO2} = 0\,\frac{kJ}{hr}$$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{out} = 1.428 \times 10^{14}\,\frac{kJ}{hr}$$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$$\Delta H = -5.692 \times 10^{13}\,\frac{kJ}{hr}$$

4.3.2 *ENERGY BALANCES ACROSS THE DRYER*

The energy balances of the dryer will be calculated using

$$\Delta H = m \cdot C_p \cdot \Delta T$$

where

m = "mass"

C_p = "heat capacity" which is given as $C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3$

ΔT = "change in temperature" which is given as $\Delta T = T_{in} - T_{ref}$

ENERGY INPUT ACROSS THE DRYER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19389.47 \\ 469.43 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{in} := \left[\begin{pmatrix} 13 \\ 13 \\ 13 \\ 13 \\ 13 \end{pmatrix} + 273\right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_1} = 286\,K$

$\Delta T_1 := T_{in_1} - T_{ref}$ $\qquad \Delta T_1 = -7\,K$

$$a_1 = 0.823 \frac{kJ}{kg \cdot K}$$

$$b_1 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$$

$$d_1 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + \cdot \left(T_{in_1}\right)^3\right] \qquad C_{p1} = -1.052 \times 10^9 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$\Delta H_{CaCO3} = 1.428 \times 10^{14} \frac{kJ}{hr}$$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 286\,K$

$$\Delta T_2 := T_{in_2} - T_{ref} \qquad \Delta T_2 = -7\,K$$

$$a_2 = 1.016\,\frac{kJ}{kg \cdot K}$$

$$b_2 = 0.026\,\frac{kJ}{kg \cdot K^2}$$

$$c_2 = -7.431 \times 10^{-5}\,\frac{kJ}{kg \cdot K^3}$$

$$d_2 = 7.295 \times 10^{-8}\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3\right] \qquad C_{p2} = 4.138\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \qquad \Delta H_{H2O} = -13598.963\,\frac{kJ}{hr}$$

Energy of impurities

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 286\,K$

$$\Delta T_3 := T_{in_3} - T_{ref} \qquad \Delta T_3 = -7\,K$$

$$a_3 = 0.253\,\frac{kJ}{kg \cdot K}$$

$$b_3 = 0\,\frac{kJ}{kg \cdot K^2}$$

$$c_3 = 0\,\frac{kJ}{kg \cdot K^3}$$

$$d_3 = 0\,\frac{kJ}{kg \cdot K^4}$$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3\right]$ $\qquad C_{p3} = 0.381 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$ $\qquad \Delta H_{Impurities} = -1470.012 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 286\,K$

$\Delta T_4 := T_{in_4} - T_{ref}$ $\qquad \Delta T_4 = -7\,K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right]$ $\qquad C_{p4} = -6.593 \times 10^8 \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$ $\qquad \Delta H_{CaO} = 0 \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} = 286\,K$

$\Delta T_5 := T_{in_5} - T_{ref}$ $\qquad \Delta T_5 = -7\,K$

$a_5 = 0.82 \frac{kJ}{kg \cdot K}$

$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$

$c_5 = -6.56 \times 10^{-7} \mathrm{K} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^4}$

$d_5 = 1.696 \times 10^{-10} \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^4}$

$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right]$ $C_{p5} = 1.046 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}}$

$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$

$\Delta H_{CO2} = 0 \frac{\mathrm{kJ}}{\mathrm{hr}}$

Total energy in: $\Delta H_{in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$\Delta H_{in} = 1.428 \times 10^{14} \frac{\mathrm{kJ}}{\mathrm{hr}}$

ENERGY OUTPUT ACROSS THE DRYER

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 19389.47 \\ 0.00 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{\mathrm{kg}}{\mathrm{hr}} \quad \text{and} \quad T_{out} := \left[\begin{pmatrix} 1000 \\ 1000 \\ 1000 \\ 1000 \\ 1000 \end{pmatrix} + 273\right] \cdot \mathrm{K} \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $T_{ref} := (20 + 273) \cdot \mathrm{K}$

Outlet temperature: $T_{out_1} = 1273\,\mathrm{K}$

$\Delta T_1 := T_{out_1} - T_{ref}$ $\Delta T_1 = 980\,\mathrm{K}$

$a_1 = 0.823 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}}$

$b_1 = 0 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^2}$

$c_1 = -12858.427 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^3}$

$d_1 = 0 \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right]$ $C_{p1} = -2.084 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$ $\Delta H_{CaCO3} = -3.959 \times 10^{17} \frac{kJ}{hr}$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 1273\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$ $\Delta T_2 = 980\,K$

$a_2 = 1.016 \frac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3\right]$ $C_{p2} = 64.434 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$ $\Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 1273\,K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\Delta T_3 = 980\,K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3\right]$ $\qquad C_{p3} = 0.822 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = 4.439 \times 10^5 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 1273 K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\qquad \Delta T_4 = 980 K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right]$ $\qquad C_{p4} = -1.306 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$

$\Delta H_{CaO} = 0 \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 1273 K$

$\Delta T_5 := T_{out_5} - T_{ref}$ $\qquad \Delta T_5 = 980 K$

$$a_5 = 0.82\,\frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001\,\frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7}\,K\,\frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10}\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right] \qquad C_{p5} = 1.332\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$\Delta H_{CO2} = 0\,\frac{kJ}{hr}$$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{out} = -3.959 \times 10^{17}\,\frac{kJ}{hr}$$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$$\Delta H = -3.961 \times 10^{17}\,\frac{kJ}{hr}$$

4.3.3 ENERGY BALANCES ACROSS THE CRUSHER

The energy balances of the crusher will be calculated using

$$\Delta H = m \cdot C_p \cdot \Delta T$$

where

m = "mass"

C_p = "heat capacity" which is given as $C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3$

ΔT = "change in temperature" which is given as $\Delta T = T_{in} - T_{ref}$

ENERGY INPUT ACROSS THE CRUSHER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19389.47 \\ 0.00 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \quad \text{and} \quad T_{in} := \left[\begin{pmatrix} 1000 \\ 1000 \\ 1000 \\ 1000 \\ 1000 \end{pmatrix} + 273\right] \cdot K \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_1} = 1273\,K$

$\Delta T_1 := T_{in_1} - T_{ref}$ $\Delta T_1 = 980\,K$

$a_1 = 0.823 \frac{kJ}{kg \cdot K}$

$b_1 = 0 \frac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$

$d_1 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + d_1 \cdot \left(T_{in_1}\right)^3\right]$ $C_{p1} = -2.084 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = -3.959 \times 10^{17} \frac{kJ}{hr}$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 1273\,K$

$\Delta T_2 := T_{in_2} - T_{ref}$ $\Delta T_2 = 980\,K$

$a_2 = 1.016 \frac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3\right]$

$C_{p2} = 64.434 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$

$\Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 1273 K$

$\Delta T_3 := T_{in_3} - T_{ref}$

$\Delta T_3 = 980 K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3\right]$

$C_{p3} = 0.822 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = 4.439 \times 10^5 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 1273 K$

$\Delta T_4 := T_{in_4} - T_{ref}$

$\Delta T_4 = 980 K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$$d_4 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right]$$

$$C_{p4} = -1.306 \times 10^{10} \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$\Delta H_{CaO} = 0 \frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} = 1273 K$

$$\Delta T_5 := T_{in_5} - T_{ref}$$

$$\Delta T_5 = 980 K$$

$$a_5 = 0.82 \frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right]$$

$$C_{p5} = 1.332 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$\Delta H_{CO2} = 0 \frac{kJ}{hr}$$

Total energy in: $\Delta H_{in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{in} = -3.959 \times 10^{17} \frac{kJ}{hr}$$

ENERGY OUTPUT ACROSS THE CRUSHER

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 19098.63 \\ 0.00 \\ 542.80 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{out} := \left[\begin{pmatrix} 1007 \\ 1007 \\ 1007 \\ 1007 \\ 1007 \end{pmatrix} + 273\right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_1} = 1280\,K$

$\Delta T_1 := T_{out_1} - T_{ref}$ $\qquad \Delta T_1 = 987\,K$

$a_1 = 0.823 \dfrac{kJ}{kg \cdot K}$

$b_1 = 0 \dfrac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427 \dfrac{kJ}{kg \cdot K^3}$

$d_1 = 0 \dfrac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right]$ $\qquad C_{p1} = -2.107 \times 10^{10} \dfrac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = -3.971 \times 10^{17} \dfrac{kJ}{hr}$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 1280\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$ $\qquad \Delta T_2 = 987\,K$

$a_2 = 1.016 \dfrac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3\right]$ $C_{p2} = 65.786 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$

$\Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 1280 K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\Delta T_3 = 987 K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3\right]$ $C_{p3} = 0.825 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = 4.42 \times 10^5 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 1280 K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\Delta T_4 = 987 K$

$$a_4 = 0.746 \frac{kJ}{kg \cdot K}$$

$$b_4 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$$

$$d_4 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right] \qquad C_{p4} = -1.321 \times 10^{10} \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \qquad \Delta H_{CaO} = 0 \frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 1280 K$

$$\Delta T_5 := T_{out_5} - T_{ref} \qquad \Delta T_5 = 987 K$$

$$a_5 = 0.82 \frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right] \qquad C_{p5} = 1.333 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \qquad \Delta H_{CO2} = 0 \frac{kJ}{hr}$$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{out} = -3.971 \times 10^{17} \frac{kJ}{hr}$$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$$\Delta H = -1.178 \times 10^{15} \frac{kJ}{hr}$$

4.3.4 ENERGY BALANCES ACROSS THE SCREENER

The energy balances of the screener will be calculated using

$$\Delta H = m \cdot C_p \cdot \Delta T$$

where

$m =$ "mass"

$C_p =$ "heat capacity" which is given as $C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3$

$\Delta T =$ "change in temperature" which is given as $\Delta T = T_{in} - T_{ref}$

ENERGY INPUT ACROSS THE SCREENER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19098.63 \\ 0.00 \\ 542.80 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{in} := \left[\begin{pmatrix} 1007 \\ 1007 \\ 1007 \\ 1007 \\ 1007 \end{pmatrix} + 273\right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_1} = 1280\,K$

$\Delta T_1 := T_{in_1} - T_{ref}$ $\qquad\qquad \Delta T_1 = 987\,K$

$$a_1 = 0.823 \frac{kJ}{kg \cdot K}$$

$$b_1 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$$

$$d_1 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + d_1 \cdot \left(T_{in_1}\right)^3\right] \qquad C_{p1} = -2.107 \times 10^{10} \frac{kJ}{kg \cdot K}$$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = -3.971 \times 10^{17} \frac{kJ}{hr}$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 1280 K$

$\Delta T_2 := T_{in_2} - T_{ref}$

$\Delta T_2 = 987 K$

$a_2 = 1.016 \frac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3 \right]$

$C_{p2} = 65.786 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$

$\Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 1280 K$

$\Delta T_3 := T_{in_3} - T_{ref}$

$\Delta T_3 = 987 K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3\right]$

$C_{p3} = 0.825 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = 4.42 \times 10^5 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 1280\,K$

$\Delta T_4 := T_{in_4} - T_{ref}$

$\Delta T_4 = 987\,K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right]$

$C_{p4} = -1.321 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$

$\Delta H_{CaO} = 0 \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} = 1280\,K$

$\Delta T_5 := T_{in_5} - T_{ref}$

$\Delta T_5 = 987\,K$

$a_5 = 0.82 \frac{kJ}{kg \cdot K}$

$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$

$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$

$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$

$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right]$ $\qquad C_{p5} = 1.333 \frac{kJ}{kg \cdot K}$

$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$ $\qquad \Delta H_{CO2} = 0 \frac{kJ}{hr}$

Total energy in: $\quad \Delta H_{in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$\Delta H_{in} = -3.971 \times 10^{17} \frac{kJ}{hr}$

ENERGY OUTPUT ACROSS THE SCREENER

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 18143.69 \\ 0.00 \\ 515.66 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \quad \text{and} \quad T_{out} := \left[\begin{pmatrix} 1200 \\ 1200 \\ 1200 \\ 1200 \\ 1200 \end{pmatrix} + 273\right] \cdot K \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $\quad T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $\quad T_{out_1} = 1473\,K$

$\Delta T_1 := T_{out_1} - T_{ref}$ $\qquad \Delta T_1 = 1180\,K$

$a_1 = 0.823 \frac{kJ}{kg \cdot K}$

$b_1 = 0 \frac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$

$d_1 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right]$ $\qquad C_{p1} = -2.79 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$

$\Delta H_{CaCO3} = -5.973 \times 10^{17} \frac{kJ}{hr}$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 1473\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$ $\qquad \Delta T_2 = 1180\,K$

$a_2 = 1.016 \frac{kJ}{kg \cdot K}$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3 \right]$ $\qquad C_{p2} = 111.517 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$ $\qquad \Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 1473\,K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\qquad \Delta T_3 = 1180\,K$

$a_3 := 0.253 \frac{kJ}{kg \cdot K}$

$b_3 := 0 \frac{kJ}{kg \cdot K^2}$

$c_3 := 0 \frac{kJ}{kg \cdot K^3}$

$d_3 := 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3 \right]$ $\qquad C_{p3} = 0.911 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$

$\Delta H_{Impurities} = 5.545 \times 10^5 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 1473\,K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\Delta T_4 = 1180\,K$

$a_4 := 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right]$ $C_{p4} = -1.749 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$

$\Delta H_{CaO} = 0 \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 1473\,K$

$\Delta T_5 := T_{out_5} - T_{ref}$ $\Delta T_5 = 1180\,K$

$a_5 = 0.82 \frac{kJ}{kg \cdot K}$

$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$

$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$

$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right] \qquad C_{p5} = 1.356 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$\Delta H_{CO2} = 0 \frac{kJ}{hr}$$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{out} = -5.973 \times 10^{17} \frac{kJ}{hr}$$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$$\Delta H = -2.002 \times 10^{17} \frac{kJ}{hr}$$

4.3.5 ENERGY BALANCES ACROSS THE FURNACE

The energy balances of the furnace will be calculated using

$$H = m \cdot c_p \cdot \Delta T + m \cdot H_f$$

where

$$C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3$$

$$H_f = \text{"Heat of formation"}$$

ENERGY INPUT ACROSS THE FURNACE

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 18143.69 \\ 0.00 \\ 515.66 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \quad \text{and} \quad T_{in} := \left[\begin{pmatrix} 1011 \\ 1011 \\ 1011 \\ 1011 \\ 1011 \end{pmatrix} + 273\right] \cdot K \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_1} = 1284\,K$

$$\Delta T_1 := T_{in_1} - T_{ref} \qquad \Delta T_1 = 991\,K$$

$$a_1 = 0.823 \frac{kJ}{kg \cdot K}$$

$$b_1 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$$

$$d_1 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + d_1 \cdot \left(T_{in_1}\right)^3\right] \qquad C_{p1} = -2.12 \times 10^{10} \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaCO3} := m'_1 \cdot \left(C_{p1} \cdot \Delta T_1 + H_{f_1}\right) \qquad \Delta H_{CaCO3} = -3.812 \times 10^{17} \frac{kJ}{hr}$$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 1284 K$

$$\Delta T_2 := T_{in_2} - T_{ref} \qquad \Delta T_2 = 991 K$$

$$a_2 = 1.016 \frac{kJ}{kg \cdot K}$$

$$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$$

$$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$$

$$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$$

$$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3\right] \qquad C_{p2} = 66.567 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{H2O} := m'_2 \cdot \left(C_{p2} \cdot \Delta T_2 + H_{f_2}\right) \qquad \Delta H_{H2O} = 0 \frac{kJ}{hr}$$

Energy of impurities input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 1284 K$

$$\Delta T_3 := T_{in_3} - T_{ref} \qquad \Delta T_3 = 991 K$$

$$a_3 = 0.253 \frac{kJ}{kg \cdot K}$$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3\right]$ $C_{p3} = 0.827 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot \left(C_{p3} \cdot \Delta T_3 + H_{f_3}\right)$ $\Delta H_{Impurities} = -6.891 \times 10^6 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 1284 K$

$\Delta T_4 := T_{in_4} - T_{ref}$ $\Delta T_4 = 991 K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right]$ $C_{p4} = -1.329 \times 10^{10} \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot \left(C_{p4} \cdot \Delta T_4 + H_{f_4}\right)$ $\Delta H_{CaO} = 0 \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} = 1284 K$

$\Delta T_5 := T_{in_5} - T_{ref}$ $\Delta T_5 = 991 K$

$$a_5 = 0.82 \frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right] \qquad C_{p5} = 1.333 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot \left(C_{p5} \cdot \Delta T_5 + H_{f_5}\right) \qquad \Delta H_{CO2} = 0 \frac{kJ}{hr}$$

Components' energy in: $\Delta H_{Comp\_in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{Comp\_in} = -3.812 \times 10^{17} \frac{kJ}{hr}$$

Total energy in:

The total energy into the furnace will be the sum of the total energy of the components and the energy supplied by the fuel passed to the furnace. Given the energy of the fuel (natural gas) to be

$$H_{fuel} := 35615 \cdot \frac{kJ}{hr}$$

$$H_{in} := \Delta H_{Comp\_in} + H_{fuel} \qquad H_{in} = -3.812 \times 10^{17} \frac{kJ}{hr}$$

ENERGY OUTPUT ACROSS THE FURNACE

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 10160.47 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \quad \text{and} \quad T_{out} := \left[\begin{pmatrix} 1000 \\ 1000 \\ 1000 \\ 1000 \\ 1000 \end{pmatrix} + 273\right] \cdot K \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_1} = 1273 K$

$\Delta T_1 := T_{out_1} - T_{ref}$ $\Delta T_1 = 980\,K$

$a_1 = 0.823 \dfrac{kJ}{kg \cdot K}$

$b_1 = 0 \dfrac{kJ}{kg \cdot K^2}$

$c_1 = -12858.427 \dfrac{kJ}{kg \cdot K^3}$

$d_1 = 0 \dfrac{kJ}{kg \cdot K^4}$

$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right]$ $C_{p1} = -2.084 \times 10^{10} \dfrac{kJ}{kg \cdot K}$

$\Delta H_{CaCO3} := m'_1 \cdot \left(C_{p1} \cdot \Delta T_1 + H_{f_1}\right)$ $\Delta H_{CaCO3} = 0 \dfrac{kJ}{hr}$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 1273\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$ $\Delta T_2 = 980\,K$

$a_2 = 1.016 \dfrac{kJ}{kg \cdot K}$

$b_2 = 0.026 \dfrac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \dfrac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \dfrac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3\right]$ $C_{p2} = 64.434 \dfrac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot \left(C_{p2} \cdot \Delta T_2 + H_{f_2}\right)$ $\Delta H_{H2O} = 0 \dfrac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 1273\,K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\Delta T_3 = 980\,K$

$a_3 = 0.253\,\frac{kJ}{kg \cdot K}$

$b_3 = 0\,\frac{kJ}{kg \cdot K^2}$

$c_3 = 0\,\frac{kJ}{kg \cdot K^3}$

$d_3 = 0\,\frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3\right]$ $C_{p3} = 0.822\,\frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot \left(C_{p3} \cdot \Delta T_3 + H_{f_3}\right)$

$\Delta H_{Impurities} = 0\,\frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 1273\,K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\Delta T_4 = 980\,K$

$a_4 = 0.746\,\frac{kJ}{kg \cdot K}$

$b_4 = 0\,\frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914\,\frac{kJ}{kg \cdot K^3}$

$d_4 = 0\,\frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right]$ $C_{p4} = -1.306 \times 10^{10}\,\frac{kJ}{kg \cdot K}$

$$\Delta H_{CaO} := m'_4 \cdot \left(C_{p4} \cdot \Delta T_4 + H_{f_4}\right)$$

$$\Delta H_{CaO} = -1.301 \times 10^{17} \frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 1273 K$

$$\Delta T_5 := T_{out_5} - T_{ref}$$

$$\Delta T_5 = 980 K$$

$$a_5 = 0.82 \frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right]$$

$$C_{p5} = 1.332 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot \left(C_{p5} \cdot \Delta T_5 + H_{f_5}\right)$$

$$\Delta H_{CO2} = 0 \frac{kJ}{hr}$$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{out} = -1.301 \times 10^{17} \frac{kJ}{hr}$$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$$\Delta H = 2.671 \times 10^{17} \frac{kJ}{hr}$$

4.3.6 ENERGY BALANCES ACROSS THE COOLER

The energy balances of the cooler will be calculated using

$$\Delta H = m \cdot C_p \cdot \Delta T$$

where

m = "mass"

C_p = "heat capacity" which is given as $C_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3$

ΔT = "change in temperature" which is given as $\Delta T = T_{in} - T_{ref}$

ENERGY INPUT ACROSS THE COOLER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 10160.47 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{in} := \left[\begin{pmatrix} 1000 \\ 1000 \\ 1000 \\ 1000 \\ 1000 \end{pmatrix} + 273 \right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_1} = 1273\,K$

$\Delta T_1 := T_{in_1} - T_{ref}$ $\qquad \Delta T_1 = 980\,K$

$$a_1 = 0.823 \frac{kJ}{kg \cdot K}$$

$$b_1 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$$

$$d_1 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p1} := \left[a_1 + b_1 \cdot T_{in_1} + c_1 \cdot \left(T_{in_1}\right)^2 + d_1 \cdot \left(T_{in_1}\right)^3 \right] \qquad C_{p1} = -2.084 \times 10^{10} \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \qquad \Delta H_{CaCO3} = 0 \frac{kJ}{hr}$$

Energy of moisture (H_2O) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_2} = 1273\,K$

$\Delta T_2 := T_{in_2} - T_{ref}$ $\qquad \Delta T_2 = 980\,K$

$$a_2 = 1.016 \frac{kJ}{kg \cdot K}$$

$$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$$

$c_2 = -7.431 \times 10^{-5} \dfrac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \dfrac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{in_2} + c_2 \cdot \left(T_{in_2}\right)^2 + d_2 \cdot \left(T_{in_2}\right)^3\right]$ $\qquad C_{p2} = 64.434 \dfrac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$ $\qquad \Delta H_{H2O} = 0 \dfrac{kJ}{hr}$

Energy of impurities input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_3} = 1273\,K$

$\Delta T_3 := T_{in_3} - T_{ref}$ $\qquad \Delta T_3 = 980\,K$

$a_3 = 0.253 \dfrac{kJ}{kg \cdot K}$

$b_3 = 0 \dfrac{kJ}{kg \cdot K^2}$

$c_3 = 0 \dfrac{kJ}{kg \cdot K^3}$

$d_3 = 0 \dfrac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{in_3} + c_3 \cdot \left(T_{in_3}\right)^2 + d_3 \cdot \left(T_{in_3}\right)^3\right]$ $\qquad C_{p3} = 0.822 \dfrac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$ $\qquad \Delta H_{Impurities} = 0 \dfrac{kJ}{hr}$

Energy of calcium oxide (CaO) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_4} = 1273\,K$

$\Delta T_4 := T_{in_4} - T_{ref}$ $\qquad \Delta T_4 = 980\,K$

$a_4 = 0.746 \dfrac{kJ}{kg \cdot K}$

$$b_4 = 0\,\frac{kJ}{kg \cdot K^2}$$

$$c_4 = -8059.914\,\frac{kJ}{kg \cdot K^3}$$

$$d_4 = 0\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p4} := \left[a_4 + b_4 \cdot T_{in_4} + c_4 \cdot \left(T_{in_4}\right)^2 + d_4 \cdot \left(T_{in_4}\right)^3\right] \qquad C_{p4} = -1.306 \times 10^{10}\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$\Delta H_{CaO} = -1.301 \times 10^{17}\,\frac{kJ}{hr}$$

Energy of carbon dioxide (CO_2) input

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Inlet temperature: $T_{in_5} := 1273\,K$

$$\Delta T_5 := T_{in_5} - T_{ref} \qquad \Delta T_5 = 980\,K$$

$$a_5 = 0.82\,\frac{kJ}{kg \cdot K}$$

$$b_5 = 0.001\,\frac{kJ}{kg \cdot K^2}$$

$$c_5 = -6.56 \times 10^{-7}\,K\,\frac{kJ}{kg \cdot K^4}$$

$$d_5 = 1.696 \times 10^{-10}\,\frac{kJ}{kg \cdot K^4}$$

$$C_{p5} := \left[a_5 + b_5 \cdot T_{in_5} + c_5 \cdot \left(T_{in_5}\right)^2 + d_5 \cdot \left(T_{in_5}\right)^3\right] \qquad C_{p5} = 1.332\,\frac{kJ}{kg \cdot K}$$

$$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$\Delta H_{CO2} = 0\,\frac{kJ}{hr}$$

Total energy in: $\Delta H_{in} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$$\Delta H_{in} = -1.301 \times 10^{17}\,\frac{kJ}{hr}$$

ENERGY OUTPUT ACROSS THE COOLER

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 10160.47 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{out} := \left[\begin{pmatrix} 100 \\ 100 \\ 100 \\ 100 \\ 100 \end{pmatrix} + 273\right] \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

Energy of calcium carbonate ($CaCO_3$) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_1} = 373\,K$

$\Delta T_1 := T_{out_1} - T_{ref}$ $\qquad \Delta T_1 = 80\,K$

$$a_1 = 0.823 \frac{kJ}{kg \cdot K}$$

$$b_1 = 0 \frac{kJ}{kg \cdot K^2}$$

$$c_1 = -12858.427 \frac{kJ}{kg \cdot K^3}$$

$$d_1 = 0 \frac{kJ}{kg \cdot K^4}$$

$$C_{p1} := \left[a_1 + b_1 \cdot T_{out_1} + c_1 \cdot \left(T_{out_1}\right)^2 + d_1 \cdot \left(T_{out_1}\right)^3\right] \qquad C_{p1} = -1.789 \times 10^9 \frac{kJ}{kg \cdot K}$$

$$\Delta H_{CaCO3} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$\Delta H_{CaCO3} = 0 \frac{kJ}{hr}$$

Energy of moisture (H_2O) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_2} = 373\,K$

$\Delta T_2 := T_{out_2} - T_{ref}$ $\qquad \Delta T_2 = 80\,K$

$$a_2 = 1.016 \frac{kJ}{kg \cdot K}$$

$b_2 = 0.026 \frac{kJ}{kg \cdot K^2}$

$c_2 = -7.431 \times 10^{-5} \frac{kJ}{kg \cdot K^3}$

$d_2 = 7.295 \times 10^{-8} \frac{kJ}{kg \cdot K^4}$

$C_{p2} := \left[a_2 + b_2 \cdot T_{out_2} + c_2 \cdot \left(T_{out_2}\right)^2 + d_2 \cdot \left(T_{out_2}\right)^3\right]$ $\qquad C_{p2} = 4.237 \frac{kJ}{kg \cdot K}$

$\Delta H_{H2O} := m'_2 \cdot C_{p2} \cdot \Delta T_2$ $\qquad \Delta H_{H2O} = 0 \frac{kJ}{hr}$

Energy of impurities output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_3} = 373\,K$

$\Delta T_3 := T_{out_3} - T_{ref}$ $\qquad \Delta T_3 = 80\,K$

$a_3 = 0.253 \frac{kJ}{kg \cdot K}$

$b_3 = 0 \frac{kJ}{kg \cdot K^2}$

$c_3 = 0 \frac{kJ}{kg \cdot K^3}$

$d_3 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p3} := \left[a_3 + b_3 \cdot T_{out_3} + c_3 \cdot \left(T_{out_3}\right)^2 + d_3 \cdot \left(T_{out_3}\right)^3\right]$ $\qquad C_{p3} = 0.42 \frac{kJ}{kg \cdot K}$

$\Delta H_{Impurities} := m'_3 \cdot C_{p3} \cdot \Delta T_3$ $\qquad \Delta H_{Impurities} = 0 \frac{kJ}{hr}$

Energy of calcium oxide (CaO) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_4} = 373\,K$

$\Delta T_4 := T_{out_4} - T_{ref}$ $\qquad \Delta T_4 = 80\,K$

$a_4 = 0.746 \frac{kJ}{kg \cdot K}$

$b_4 = 0 \frac{kJ}{kg \cdot K^2}$

$c_4 = -8059.914 \frac{kJ}{kg \cdot K^3}$

$d_4 = 0 \frac{kJ}{kg \cdot K^4}$

$C_{p4} := \left[a_4 + b_4 \cdot T_{out_4} + c_4 \cdot \left(T_{out_4}\right)^2 + d_4 \cdot \left(T_{out_4}\right)^3\right]$

$C_{p4} = -1.121 \times 10^9 \frac{kJ}{kg \cdot K}$

$\Delta H_{CaO} := m'_4 \cdot C_{p4} \cdot \Delta T_4$

$\Delta H_{CaO} = -9.115 \times 10^{14} \frac{kJ}{hr}$

Energy of carbon dioxide (CO_2) output

Reference temperature: $T_{ref} := (20 + 273) \cdot K$

Outlet temperature: $T_{out_5} = 373\, K$

$\Delta T_5 := T_{out_5} - T_{ref}$

$\Delta T_5 = 80\, K$

$a_5 = 0.82 \frac{kJ}{kg \cdot K}$

$b_5 = 0.001 \frac{kJ}{kg \cdot K^2}$

$c_5 = -6.56 \times 10^{-7} K \frac{kJ}{kg \cdot K^4}$

$d_5 = 1.696 \times 10^{-10} \frac{kJ}{kg \cdot K^4}$

$C_{p5} := \left[a_5 + b_5 \cdot T_{out_5} + c_5 \cdot \left(T_{out_5}\right)^2 + d_5 \cdot \left(T_{out_5}\right)^3\right]$

$C_{p5} = 1.097 \frac{kJ}{kg \cdot K}$

$\Delta H_{CO2} := m'_5 \cdot C_{p5} \cdot \Delta T_5$

$\Delta H_{CO2} = 0 \frac{kJ}{hr}$

Total energy out: $\Delta H_{out} := \Delta H_{CaCO3} + \Delta H_{H2O} + \Delta H_{Impurities} + \Delta H_{CaO} + \Delta H_{CO2}$

$\Delta H_{out} = -9.115 \times 10^{14} \frac{kJ}{hr}$

Heat load: $\Delta H := \Delta H_{out} - \Delta H_{in}$

$\Delta H = 1.291 \times 10^{17} \frac{kJ}{hr}$

4.4 *MOMENTUM BALANCE*

Momentum is a fundamental quantity characterizing the motion of any object (see Mechanics). It is the product of the mass of a moving particle multiplied by its linear velocity. Momentum is a vector quantity, which means that it has both magnitude and direction. The total momentum of a system made up of a collection of objects is the vector sum of all the individual objects' momenta.(Encarta, 2004)

$$\text{Momentum} = m \cdot v$$

Mathematically, momentum is given as
where m is the mass of the body and v is its velocity.

For this plant, only conveyor is moving. So, it is the only unit having velocity, hence, it is the only unit that will have the momentum balance because all other units have their momentum to be equal to zero since they are stationary.

Assuming that

mass of conveyor before loading, $v_l := 50 \cdot \frac{km}{hr}$

mass of conveyor before loading, $m_l := 101000 \cdot kg$

The momentum of the conveyor before loading the chalk is therefore calculated as

$$\text{Momentum}_l := m_l \cdot v_l \qquad \text{Momentum}_l = 1.403 \times 10^6 N \cdot s$$

Given that the masses of the materials in the conveyor is

$$m_{conveyor} := \begin{pmatrix} 19585.32 \\ 474.17 \\ 556.64 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr}$$

The total mass of the materials is calculated as $M_{material} := \sum m_{conveyor}$

$$M_{material} = 20616.13 \frac{kg}{hr}$$

When the conveyor is loaded with the material, the total mass of the conveyor with the material is

$M_{Tconveyor} := m_1 + M_{material} \cdot hr$

$M_{Tconveyor} = 1.216 \times 10^5 \, kg$

$m_2 := M_{Tconveyor}$

Momentum balance equation is given as

$m_1 \cdot v_1 = m_2 \cdot v_2$

$v_2 := \frac{m_1 \cdot v_1}{m_2}$

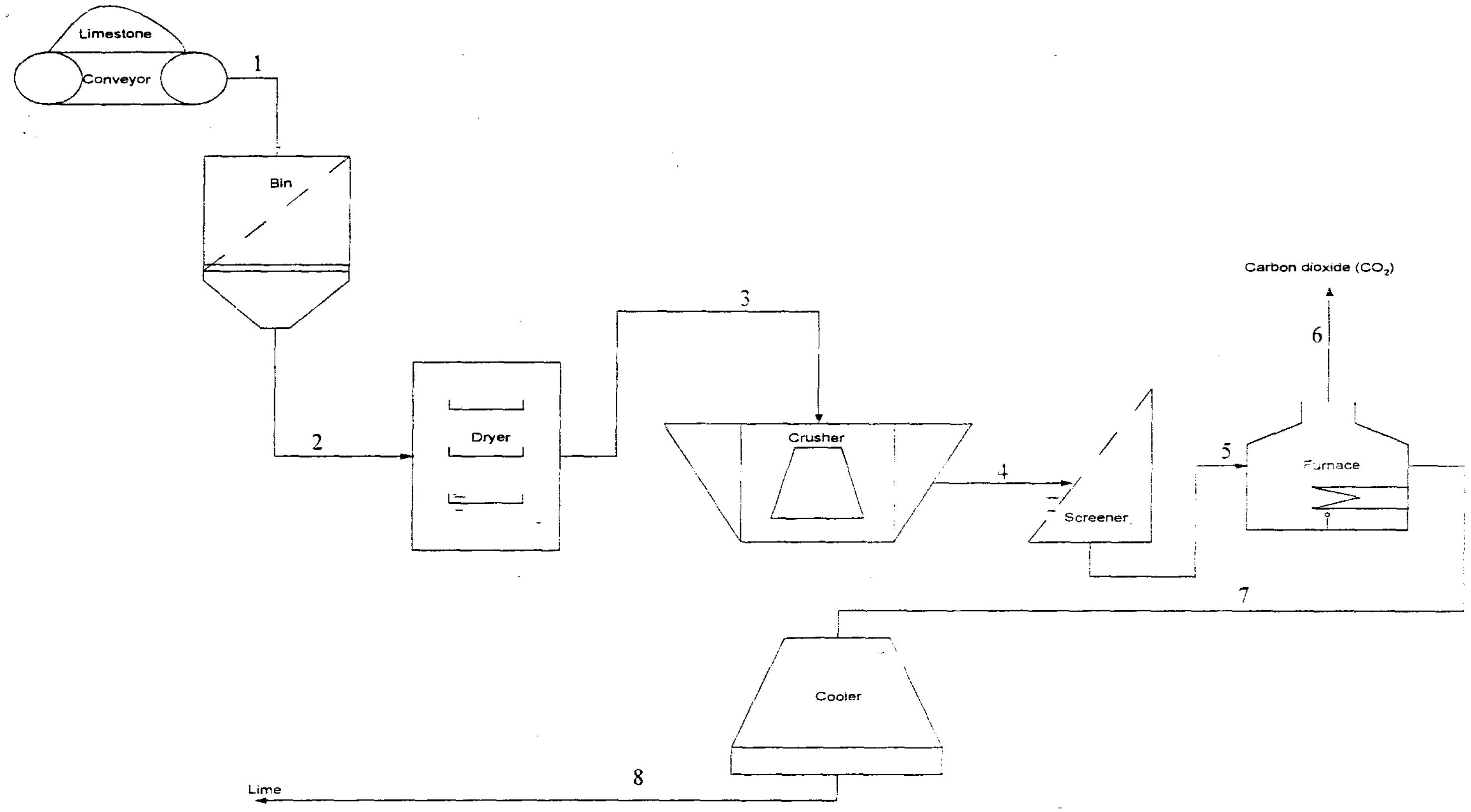
$v_2 = 11.534 \frac{m}{s}$

$v_2 = 41.524 \frac{km}{hr}$

This means that the conveyor must move at the rate of $v_2 = 41.524 \frac{km}{hr}$ after it is loaded with the limeston

5.0 FLOWSHEETING

GROUP C PLANT DESIGN	*Title: Lime production from limestone* *Client: Chemical Engineering Department, FUT, Minna*	*Date: 20th Nov., 2005*



Flows (kg/hr)

Line No.	1	2	3	4	5	6	7	8
Component								
$CaCO_3$	19389.47	19389.47	19389.47	19098.63	18143.69	0.00	0.00	0.00
H_2O	469.43	469.43	0.00	0.00	0.00	0.00	0.00	0.00
Impurities	551.07	551.07	551.07	542.80	515.66	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00	10160.47	10160.47
CO_2	0.00	0.00	0.00	0.00	0.00	7983.23	0.00	0.00
	20409.97	20409.97	19940.54	19641.43	18659.36	7983.23	10160.47	10160.47

CHAPTER SIX

6.0 DESIGN OF EQUIPMENTS

6.1 CHEMICAL ENGINEERING DESIGN OF EQUIPMENTS

6.1.1 DESIGN OF BIN

Type: Cylindrical-top and cone-based container

Material of construction: Carbon steel

Denoting the mass of the components by m', the density by ρ, the molecular weight by molwt; and amount in moles n.

The masses, densities, molecular weights and number of moles of the components in the bin are thus;

$$\begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix} \qquad m' := \begin{pmatrix} 19389.47 \\ 469.43 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \rho := \begin{pmatrix} 2930 \\ 1000 \\ 2250 \\ 2620 \\ 1530 \end{pmatrix} \cdot \frac{kg}{m^3} \qquad molwt := \begin{pmatrix} 100.00 \\ 18.00 \\ 60.00 \\ 56.00 \\ 44.00 \end{pmatrix} \cdot \frac{kg}{kmol}$$

The number of moles of each components, n, is calculated using

$$n := \overrightarrow{\frac{m'}{molwt}}$$

$$\begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix} \qquad n = \begin{pmatrix} 193.895 \\ 26.079 \\ 9.184 \\ 0 \\ 0 \end{pmatrix} \frac{kmol}{hr}$$

The average density of the components is calculated as;

$$\rho_{av} := \left(\frac{n_1}{\sum n} \cdot \rho_1 + \frac{n_2}{\sum n} \cdot \rho_2 + \frac{n_3}{\sum n} \cdot \rho_3 + \frac{n_4}{\sum n} \cdot \rho_4 + \frac{n_5}{\sum n} \cdot \rho_5 \right)$$

$$\rho_{av} = 2683.102 \frac{kg}{m^3}$$

The total mass of the components in the bin is equal to $m_{bin} := \sum m'$

$$V_{bin} := \frac{m_{bin}}{\rho_{av}} \qquad V_{bin} = 7.607\frac{m^3}{hr}$$

The bin is cylindrical with conical bottom, hence

$V_{soap\_blender}$ = "volume of cylindrical top + volume of conical bottom"

$$V_{top} = \pi \cdot R^2 \cdot H$$

$$V_{bottom} = \frac{1}{3}\pi \cdot R^2 \cdot h$$

Total volume of the bin is then

$$V_{bin} = V_{top} + V_{bottom}$$

$$V_{bin} = \pi \cdot R^2 \cdot H + \frac{1}{3}\pi \cdot R^2 \cdot h$$

$$R = \frac{D}{2}$$

$$V_{bin} = \pi \cdot \left(\frac{D}{2}\right)^2 \cdot H + \frac{1}{3}\pi \cdot \left(\frac{D}{2}\right)^2 \cdot h$$

Assuming that $\frac{H}{D} = r$ and $h = k \cdot H$

where

$r := 2$ and $k := 0.23$

That is,

$H = r \cdot D$ and $h = kH$

$h = k \cdot D$ implies that $h = k \cdot r \cdot D$

So,

$$h = k \cdot r \cdot D$$

After ubstitution,

$$V_{bin} = \pi \cdot \left(\frac{D_{bin}}{2}\right)^2 \cdot H + \frac{1}{3}\pi \cdot \left(\frac{D_{bin}}{2}\right)^2 \cdot h$$

becomes

$$V_{bin} = \pi \cdot \left(\frac{D_{bin}}{2}\right)^2 \cdot r \cdot D_{bin} + \frac{1}{3}\pi \cdot \left(\frac{D_{bin}}{2}\right)^2 \cdot k \cdot r \cdot D$$

$$V_{bin} = \frac{\pi \cdot r}{4} \cdot \left(D_{bin}\right)^3 + \frac{\pi \cdot k \cdot r}{12} \cdot \left(D_{bin}\right)^3$$

$$V_{bin} = \left(D_{bin}\right)^3 \cdot \left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)$$

$$\left(D_{bin}\right)^3 = \frac{V_{bin}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)}$$

Making the diameter of the bin (D_{bin}) the subject of the formular

$$D_{bin} = \left[\frac{V_{bin}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)}\right]^{\frac{1}{3}}$$

$$V_{bin} := V_{bin} \cdot hr$$

$$D_{bin} := \left[\frac{V_{bin}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)}\right]^{\frac{1}{3}} \qquad D_{bin} = 1.651\,m$$

Based on the assumption that H = 2D,

$$H_{top} := r \cdot D_{bin} \qquad H_{top} = 3.301\,m$$

$$h_{bottom} := k \cdot H_{top} \qquad h_{bottom} = 0.759\,m$$

Total height of the bin is therefore,

$$H_{bin} := H_{top} + h_{bottom} \qquad H_{bin} = 4.061\,m$$

The area of the bin is thus calculated as the sum of the area of cylindrical and the frustrum part. That is,

$$A_{bin} := \left[2 \cdot \pi \cdot \left(\frac{D_{bin}}{2}\right) \cdot H_{top} + 2 \cdot \pi \cdot \left(\frac{D_{bin}}{2}\right)^2\right] + \pi \cdot \frac{D_{bin}}{2} \cdot h_{bottom}$$

$$A_{bin} = 23.369\,m^2$$

6.1.2 DESIGN OF DRYER

The rotary drier forms an important part of the plant. The drier has a capability of removing the moisture associated with the chalk (raw material) lime. The drier is a counter current drier,with air as the heating medium. The Relative Humidity (RH) of the air entering is 15%. The air entering is heated to a temperature of 170°C.

Amount of water in dryer feed, $W_f := 469.43 \cdot \frac{kg}{hr}$

Solid in dryer feed, $S_f := 19940.54 \cdot \frac{kg}{hr}$

Water content in dryer output, $W_p := 0 \cdot \frac{kg}{hr}$

Hence, water removed by the dryer is

$W_d := W_f - W_p$ $\qquad\qquad$ $W_d = 469.43 \frac{kg}{hr}$

Inlet air temperature, $T_{ia} := (170 + 273) \cdot K$

Outlet air temperature, $T_{oa} := (90 + 273) \cdot K$

Inlet temperature of feed, $T_{if} := (27 + 273) \cdot K$

Discharge temperature, $T_d := (1000 + 273) \cdot K$

The temperature of the air leaving the dryer should be selected on the basis of an economic balance between dryer and fuel cost. It has been that dryers are most economically operated when the total Number of Transfer Units (NTU) range from 1.5 to 2.0. Assuming that

So, assuming that

$NTU := 1$

Knowing that,

$$NTU = \ln\left[\frac{(t_{g1} - t_w)}{t_{g2} - t_w}\right]$$

$t_{g1} := T_{ia}$

$t_w := T_d$

$$t_{g2} := \frac{\left(\exp(NTU) \cdot t_w + t_{g1} - t_w\right)}{\exp(NTU)} \qquad t_{g2} = 967.66\,K$$

The heat balance of the dryer has revealed that the total heat required to raise the product to the

discharge temperature is

$$Q_t := -4.107 \times 10^{17} \cdot \frac{kJ}{hr} \qquad Q_t = -4.107 \times 10^{17}\,\frac{kJ}{hr}$$

The Log Mean Temperature Difference (LMTD) across the dryer, ΔT_m is

$$\Delta T_m := \left| \frac{\left[\left(T_{ia} - T_{if}\right) - \left(T_d - T_{oa}\right)\right]}{\ln\left[\frac{\left(T_{ia} - T_{if}\right)}{\left(T_d - T_{oa}\right)}\right]} \right| \qquad \Delta T_m = 414.46\,K$$

The minimum velocity of air is set based on the particle size. Air flow rate of

$v_{air} := 23 \times 10^{12} \cdot \frac{kg}{hr \cdot m^2}$ is sufficient for lime. Hence this will be used in application.

The minimum velocity is used since it gives the smallest possible size of dryer.

Amount of air required is calculated using the relatioship

$$Q_t = M \cdot C_p \cdot \Delta T$$

$$M = \frac{|Q_t|}{\left(C_p \cdot \Delta T\right)}$$

Given that

$$|Q_t| = 4.107 \times 10^{17}\,\frac{kJ}{hr}$$

$$C_p := 4.187 \cdot \frac{kJ}{kg \cdot K}$$

$$\Delta T := T_{ia} - T_{oa}$$

So,

$$M_{air} := \frac{|Q_t|}{\left(C_p \cdot \Delta T\right)} \qquad M_{air} = 1.226 \times 10^{15}\,\frac{kg}{hr}$$

Area of dryer is thus calculated to be

$$A_{dryer} := \frac{M_{air}}{v_{air}} \qquad A_{dryer} = 53.309\,m^2$$

Using the formula for the area of dryer which is

$$A_{dryer} = \pi \cdot R_{dryer}^{2}$$

where A_{dryer} is the area of dryer

R_{dryer} is the radius of dryer

Denoting the diameter of the dryer as D_{dryer}

$$A_{dryer} = \pi \left(\frac{D_{dryer}}{2}\right)^{2}$$

$$A_{dryer} = \pi \cdot \frac{D_{dryer}^{2}}{4}$$

$$4 \cdot A_{dryer} = \pi \cdot D_{dryer}^{2}$$

$$D_{dryer}^{2} = \frac{4 \cdot D_{dryer}}{\pi}$$

The diameter of dryer is thus equal to

$$D_{dryer} := \sqrt{\frac{4 \cdot A_{dryer}}{\pi}} \qquad D_{dryer} = 8.239\,\mathrm{m}$$

Length of transfer unit has been related to mass velocity and diameter by the following relation,

$$LTU = 0.0064 \cdot C_p \cdot (G)^{0.84} \cdot d_{dryer}$$

where G is the mass velocity which is equal to $G := v_{air}$, that is,

$$G = 5.52 \times 10^{14} \frac{\mathrm{kg}}{\mathrm{day} \cdot \mathrm{m}^2}$$

So.

$$LTU := 194 \cdot 10^{-9} \cdot \frac{C_p}{\frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}}} \cdot \left(\frac{G}{\frac{\mathrm{kg}}{\mathrm{day} \cdot \mathrm{m}^2}}\right)^{0.4} \cdot D_{dryer}$$

$$LTU = 5.276\,\mathrm{m}$$

Length of the dryer is given as

$$L_{dryer} := LTU \cdot NTU \qquad L_{dryer} = 5.276\,\mathrm{m}$$

6.1.3 DESIGN OF CRUSHER

Type: Jaw crusher

Material of construction: Steel

The crusher is used to reduce the size of the chalk with the aid of the crushing ability it posseses. The crushing ability of the crusher is carried by the rolls inside the crusher. Therefore, the design of the crusher will take the space of the rolls into account so as not to underestimate the capacity of the crusher.

Given the the amount of mass and characteristics of materials in the crusher to be:

$$\begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix} \qquad M := \begin{pmatrix} 19389.47 \\ 0.00 \\ 551.07 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \rho := \begin{pmatrix} 2930 \\ 1000 \\ 2250 \\ 2620 \\ 1530 \end{pmatrix} \cdot \frac{kg}{m^3} \qquad molwt := \begin{pmatrix} 100.00 \\ 18.00 \\ 60.00 \\ 56.00 \\ 44.00 \end{pmatrix} \cdot \frac{kg}{kmol}$$

The average density of the materials in the crusher can be calculated as;

$$\rho_{av} := \frac{\left(M_1 \cdot \rho_1 + M_2 \cdot \rho_2 + M_3 \cdot \rho_3 + M_4 \cdot \rho_4 + M_5 \cdot \rho_5\right)}{\left(\sum M\right)} \qquad \rho_{av} = 2911.208 \frac{kg}{m^3}$$

The total mass of the materials in the crusher is given as

$$\sum M = 19940.54 \frac{kg}{hr}$$

So, the volume is calculated to be

$$V_{crusher} := \frac{\sum M}{\rho_{av}} \qquad V_{crusher} = 6.85 \frac{m^3}{hr}$$

The volume of the occupied by the rolls canbe given as

$$Q = \frac{d \cdot L \cdot s}{2.96}$$

where

Q is the capacity of the crusher occupied by the rolls in

d is the distance between the rolls

L is the length of rolls

s is the peripheral speed

Given that,

$d := 1.33 \cdot cm$

$L := 1.15 \cdot cm$

$s' := 7 \cdot \frac{cm}{min}$

$Q_{crusher} := \frac{(d \cdot L \cdot s')}{2.96}$ $\qquad Q_{crusher} = 0 \frac{m^3}{hr}$

The total volume of the crusher is thus

$Q_{crusher} := Q_{crusher}$

$V_{Tcrusher} := V_{crusher} + Q_{crusher}$ $\qquad V_{Tcrusher} = 6.85 \frac{m^3}{hr}$

The volume of the crusher is given as:

$$V = \pi \cdot r^2 \cdot h$$

and, since

$$r = \frac{d}{2}$$

$$V = \pi \cdot \left(\frac{d}{2}\right)^2 \cdot h$$

$$V = \pi \cdot \frac{d^2}{4} \cdot h$$

Let h = kd, where k is a constant

substituting for h,

$$V = \pi \cdot \frac{d^2}{4} \cdot (k \cdot d)$$

$$4 \cdot V = k \cdot \pi \cdot d^3$$

Making d the subject of the formular

$$d = \left(\frac{4 \cdot V}{k \cdot \pi}\right)^{\frac{1}{3}}$$

assuming that $k := 1.87$

$$V_{Tcrusher} := V_{Tcrusher} \cdot hr$$

$$d_{crusher} := \left(\frac{4 \cdot V_{Tcrusher}}{k \cdot \pi}\right)^{\frac{1}{3}} \qquad d_{crusher} = 1.671\,m$$

From

$$h_{crusher} := k \cdot d_{crusher}$$

$$h_{crusher} = 3.124\,m$$

The area of the crusher is therefore,

$$A := 2\pi \cdot \frac{d_{crusher}}{2} \cdot h_{crusher} + 2\pi \cdot \left(\frac{d_{crusher}}{2}\right)^2 \qquad A = 20.784\,m^2$$

The net power to drive a roll ball was found to be

$$E = [(1.64 \cdot L - 1) \cdot K + 1](1.64 \cdot D)^{2.5} \cdot E_2$$

where

E is the net power to drive a roll

L is the inside length of the crusher, m

D is the mean inside diameter of the crusher, m

E_2 is the net power used by a 0.6 - 0.6-m roll under similar operating conditions K is a constant which is 0.9 for rolls less than 1.5m long and 0.85 for crushers over 1.5m long

Now, choosing

$$L = 0.011\,m$$

$$K_r := 0.9$$

$$D := d_{crusher}$$

$$E_2 := 9.5 \cdot W$$

(Ernest, 1995)

So, the net power used by the roll is

$$E_{roll} := [(1.64 \cdot L - 1 \cdot m) \cdot K_r + 1m](1.64 \cdot D)^{2.5} \cdot E_2 \cdot m^{-3.5} \qquad E_{roll} = 13.811\,W$$

6.1.4 DESIGN OF SCREENER

Screening is the separation of a mixture of various sizes of grains into two or more portions by means of a screening surface, the screening surface acting as a multiple go-no-go gauge and the final portions consisting of grains of more uniform size than thoseof the original mixture.

Material that remains on a given screening surface is the oversize or plus material, material passing through the screening surface is the undersize or minus material, and material passing one screening surface and retained on a subsequent surface is the intermediate material.

The screening surface may consist of woven-wire, silk, or plasticcloth, perforated or punched plate, grizzly bars, or wedge wire sections. (Perry, 1998)

Screen Efficiency

A sound method of evaluating screen performanceis given by W. S. Tyler, Inc., Mentor, Ohio, in

its Sieve Handbook, no. 53. In this formula, when material put through the screen is the desired

product, "efficiency" is the ratio of the amount of undersize obtained to the amount of undersize in

the feed $E = \frac{R \cdot d}{b}$

where

E = "efficiency"

R = "percent of fines through the screen"

d = "percent finer than the designed size in screen fines"

b = "percent finer than the designated size in screen feed"

When the object is to recover an oversize product from the screen, efficiency may be expressed

as a ratio of the amount of oversize obtained to the amount of true oversize:

$$E = \frac{O \cdot c}{a}$$

O = "percent of oversize over the screen"

c = "percent coarser than the designated size in screen oversize"

a = "percent coarser than the designated size in screen feed"

Other formulas for the derivation of screen efficiency are used by Taggart (Handbook of Mineral Dressing) gives the formula

$$E = 100 \cdot \frac{100 \cdot (e - v)}{e \cdot (100 - v)}$$

where

E = "Efficiency"

e = "percentage of undersize in the feed"

v = "percentage of undersize in the screen oversize"

Calculation of screen efficiency

In this project, the efficiency of the screen will be given as

$$E = \frac{R \cdot d}{b}$$

when

$R := 90\%$

$d := 13\%$

$b := 15\%$

Therefore, from

$$E := \frac{R \cdot d}{b} \qquad E = 0.78$$

Estimating Screen Capacity

Various methods of predicting screening capacity have been proposed, and each has its limitations. The throughflow method of Matthews uses the following equation:

$$A = \frac{0.4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s}$$ (Perry, 1998)

where

A = "screen area"

C_t = "throughflow rate"

C_u = "unit capacity"

F_{oa} = "open-area factor"

F_s = "slotted-area factor"

Given that,

$C_t := 19641.43 \cdot \frac{kg}{hr}$

$C_u := 0.05 \cdot \frac{tonne}{hr \cdot ft^2}$ $C_u = 538.196 \frac{kg}{hr \cdot m^2}$ (Perry, 1998)

$a_1 := 0.1 \cdot cm$

$a_2 := 2 \cdot cm$

(Perry, 1998)

$d_1 := 0.15cm$

$d_2 := d_1$

$$F_{oa} := 100 \cdot \left[\frac{a_1 \cdot (a_2 + 2 \cdot a_1)}{(a_2 + 2 \cdot a_1 + 3d_2) \cdot (a_1 + d_1)}\right]$$

(Perry, 1998) $F_{oa} = 33.208$

$F_s := 0.065\% \cdot F_{oa}$

So, from,

$$A_{screener} := \frac{4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s}$$ $A_{screener} = 20.366\,m^2$

(Perry, 1998)

The diameter of the screener can be estianted from

$$D_{screener} := \sqrt{\frac{4 \cdot A_{screener}}{\pi}}$$ $D_{screener} = 5.092\,m$

Assuming the height to be 1.5 of the diameter,

$H_{screener} := 1.5 \cdot D_{screener}$ $H_{screener} = 7.638\,m$

6.1.5 DESIGN OF FURNACE

Given below is the mass in, mass out and mass of the gas out of the furnace.

$$
\begin{array}{cccc}
 & \text{mass in} & \text{mass out} & \text{mass of gas out} \\
\begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix} &
m_{in} := \begin{pmatrix} 18143.69 \\ 0.00 \\ 515.66 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} &
m_{out} := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 10160.47 \\ 0.00 \end{pmatrix} \cdot \frac{kg}{hr} &
m_{gout} := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 7983.23 \end{pmatrix} \cdot \frac{kg}{hr}
\end{array}
$$

PROPERTIES OF PROCESS FLUID

The thermal properties of the process fluid flowing through the furnace are extremely important to the furnace designer. These properties not only have a direct affect on the amount of heat transferred, they also are important in predicting the pressure loss and furnace coking rates, etc. For single phase fluids, liquid or vapor, the properties can normally be assumed to change on a straight line basis from the inlet to the outlet of the heater. Therefore, providing the designer with the properties of the process fluid at the inlet and outlet conditions will normally suffice.

The one exception to this, is the viscosity. And this problem is made even worse when an attempt to extrapolate from two given points, such as the inlet and outlet, to get a value for the process fluid at a higher temperature which may occur due to the film temperature rise in the heat absorbing tubes. The following formula may be used to correct the viscosity using the two given values.

$$\mu_{new} = A \cdot e^{\left(\frac{B}{T_{new}}\right)}$$

where

$$A = \mu_{in} \cdot e^{\left(\frac{-B}{T_{in}}\right)}$$

$$B = \frac{\ln\left(\frac{\mu_{in}}{\mu_{out}}\right)}{\left(\frac{1}{T_{in}} - \frac{1}{T_{out}}\right)}$$

μ_{new} is the corrected viscosity

μ_{in} is the inlet viscosity

μ_{out} outlet viscosity

T_{new} is the temperatre at new condition

T_{in} is the temperature at the inlet

T_{in} is the temperature at inlet

T_{out} is the temperature at outlet

In this case,

$\mu_{in} := 0.1057 \cdot \text{poise}$

$\mu_{out} := 0.107 \cdot \text{poise}$

$T_{in} := 1500 \cdot K$

$T_{out} := 1100 \cdot K$

$$B := \frac{\ln\left(\frac{\mu_{in}}{\mu_{out}}\right)}{\left(\frac{1}{T_{in}} - \frac{1}{T_{out}}\right)} \qquad B = 50.424\,K$$

$$A := \mu_{in} \cdot e^{\left(\frac{-B}{T_{in}}\right)} \qquad A = 0.01\,\frac{kg}{m \cdot s}$$

$T_{new} := 1200 \cdot K$

$$\mu_{new} := A \cdot e^{\left(\frac{B}{T_{new}}\right)} \qquad \mu_{new} = 0.011\,\frac{kg}{m \cdot s}$$

INTUBE PRESSURE DROP

The intube pressure drop may be calculated by any number of methods available today, but the following procedures should give sufficient results for furnace design. The pressure loss in furnace tubes and fittings is normally calculated by first converting the fittings to an equivalent length of pipe. Then the average properties for a segment of piping and fittings can be used to calculate a pressure drop per foot to apply to the overall equivalent length. This pressure drop per foot value can be improved by correcting it for inlet and outlet specific volumes.

The friction loss is given by:

$$\Delta_p = \frac{0.00517}{d_i} \cdot G_2 \cdot V_{lm} \cdot F \cdot L_{equiv}$$

where

Δ_p is the pressure drop

d_i is inside diameter of the tube

G is the mass velocity of fluid

V_{lm} is the log mean specific volume correction

F is the Fanning friction factor

L_{equiv} is the equivalent length of pipe run

The log mean specific volume correction is given by

$$V_{lm} = \frac{(V_2 - V_1)}{\ln\left(\frac{V_2}{V_1}\right)}$$

where

V_1 is the specific volume at start of run

V_2 is the specific volume at end of run

Given that,

$$V_1 := \sum \overrightarrow{\frac{m_{in}}{\rho}} \qquad V_1 = 6.422 \frac{m^3}{hr}$$

$$V_2 := \sum \frac{\overrightarrow{m_{out}}}{\rho}$$

$$V_2 = 3.878 \frac{m^3}{hr}$$

$$V_{lm} := \frac{(V_2 - V_1)}{\ln\left(\frac{V_2}{V_1}\right)}$$

$$V_{lm} = 0.001\, m^3 s^{-1}$$

Fanning Friction Factor:

The Moody friction factor, for a non-laminar flow, may be calculated by using the Colebrook equation relating the friction factor to the Reynolds number and relative roughness. And the Fanning friction factor is 1/4 the Moody factor. For a clean pipe or tube, the relative roughness value for an inside diameter given in inches is normally 0.0018 inch. With this, the friction factor was found to be 0.00457 (that is, $F := \frac{0.00457}{m^2 \cdot s}$).

Equivalent Length Of Return Bends:

The equivalent length of a return bend may be obtained from the following curves based on Maxwell

table and can be corrected using the Reynolds number correction factor.

$$L_{equiv} = Fact_{Nre} \cdot L_{rb}$$

where

$Fact_{Nre}$ Reynolds number correction

L_{rb} Equivalent length of return bend

If

$Fact_{Nre} := 0.115$

$L_{rb} := 2.3 \cdot m$

$L_{equiv} := Fact_{Nre} \cdot L_{rb}$

$L_{equiv} = 0.265\, m$

Given

$d_i := 0.153 \cdot m$

Assuming that, $G_2 := 1.034 \times 10^3 \cdot \frac{kg}{m^2 \cdot s}$, the friction is, therefore, calculated as

$$\Delta_p := \frac{0.00517}{d_i} \cdot G_2 \cdot V_{lm} \cdot F \cdot L_{equiv}$$

$$\Delta_p = 5.917 \times 10^{-5} s^{-1} \frac{N}{m^2}$$

HEAT TRANSFER COEFFICIENTS

The inside film coefficient needed for the thermal calculations may be estimated by several different methods. The API RP530, Appendix C provides the following methods,

For vapour flow with Re >= 10,000,

$$h_v = 0.021 \cdot \left(\frac{k}{d_i}\right) \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \left(\frac{T_b}{T_w}\right)^{0.5}$$

where

h_v is the vapour phase heat transfer coefficient

k is the thermal conductivity

T_b is the bulk temperature of vapour

T_w is the wall temperature of the vapour

Re is the Reynolds number which is calculated as $Re = \frac{d_i \cdot G}{\mu_b}$

and Pr is the Prandtl number calculated as $Pr = \frac{C_p \cdot \mu_b}{k}$

$$d_i = 0.153 m$$

$$k := 3.808 \times 10^{-5} \cdot \frac{kJ}{s \cdot m \cdot K}$$

$$G_2 = 1034 \frac{kg}{m^2 \cdot s} \qquad G := G_2$$

$$\mu_b := 5.002 \times 10^{-6} \cdot \frac{kg}{m \cdot s}$$

$$C_p := 1.279 \cdot \frac{kJ}{kg \cdot K}$$

So,

$$Re := \frac{d_i \cdot G}{\mu_b} \qquad Re = 3.163 \times 10^7$$

$$Pr := \frac{C_p \cdot \mu_b}{k} \qquad Pr = 0.168$$

$$T_b := 367 \cdot K$$

$$T_w := 378 \cdot K$$

$$h_v := 0.021 \cdot \left(\frac{k}{d_i}\right) \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \left(\frac{T_b}{T_w}\right)^{0.5} \qquad h_v = 2.523 \frac{kJ}{s \cdot m^2 \cdot K}$$

Bare Tube Pressure Loss:

For bare tubes, the method presented by Winpress (Hydrocarbon Processing, 1963) can be used. In the method,

$$\Delta P = \frac{P_v}{2} \cdot N_r$$

where,

ΔP is the pressure drop

P_v is the velocity head of gas

N_r is the number of tube rows

The velocity head can be described as,

$$P_v = 0.0002317 \cdot \left(\frac{G_n}{1000}\right) \cdot \rho_g$$

where

G_n is the mass velocity of gas

ρ_g is the density of gas

$$G_n = \frac{W_g}{A_n}$$

where

W_g is the mass gas flow

A_n is the net free area

$$A_n = A_d - \frac{d_o}{12} \cdot L_e \cdot N_t$$

$$A_d = \left(N_t \cdot \frac{P_t}{12}\right) \cdot L_e$$

A_d is the convection box area

d_o is the outside tube diameter

L_e is the tube length

P_t is the transverse pitch of tubes

N_t is the number of tubes per row

Now,

$N_t := 4$

$P_t := 0.203 \cdot m$

$L_e := 7.925 \cdot m$

$$A_d := \left(N_t \cdot \frac{P_t}{12}\right) \cdot L_e \qquad A_d = 0.536\,m^2$$

Also,

$d_o := 0.114 \cdot m$

$$A_n := A_d - \frac{d_o}{12} \cdot L_e \cdot \qquad A_n = 0.235\,m^2$$

$$W_g := \sum m_{gout}$$

$$G_n := \frac{W_g}{A_n} \qquad G_n = 9.432\,\frac{kg}{m^2 \cdot s}$$

$$\rho_g := 0.308 \cdot \frac{kg}{m^3}$$

$$P_v := \frac{0.0002317 \cdot \left(\frac{G_n}{1000}\right)^2}{\rho_g} \qquad P_v = 6.693 \times 10^{-8}\,\frac{N}{m^2}$$

$N_r := 4$

$$\Delta P := \frac{P_v}{2} \cdot N_r \qquad \Delta P = 1.339 \times 10^{-7} \, \frac{N}{m^2}$$

Fin Tube Pressure Loss:

For the fin tube pressure drop, the Escoa method will be used

$$\Delta P = \frac{\left[(f + a) \cdot G_n^{\,2} \cdot N_r\right]}{\rho_b \cdot 1.083 \cdot 10^9}$$

For inline layouts,

where

ΔP is the pressure drop

ρ_b is the density of bulk gas

ρ_{out} is the density of outlet gas

ρ_{in} is the density of inlet gas

G_n is the mass gas flow

Nr is the number of tube rows

d_o is the outside tube diameter

d_f is the outside fin diameter

$$f = C_2 \cdot C_4 \cdot C_6 \cdot \left(\frac{d_f}{d_o}\right)$$

$$a = \left[\frac{(1 + B_2)}{(4 \cdot N_r)}\right] \cdot \rho_b \cdot \left[\left(\frac{1}{\rho_{out}}\right) - \left(\frac{1}{\rho_{in}}\right)\right]$$

$$B = \frac{A_n}{A_d}$$

For staggered tubes with corbels or inlune tubes,

$$A_d = \left(\frac{N_t \cdot P_t}{12}\right) \cdot L_e$$

Net Free Area, A_n:

$$A_n = A_d - A_c \cdot L_e \cdot N_t$$

A_d is the cross sectional area of box

A_c is the fin tube cross sectional area per m,

L_e is the effective tube length

N_t is the number tubes wide

and

$$A_c = \frac{\left(d_o + 2 \cdot l_f \cdot t_f \cdot n_f\right)}{12}$$

t_f is the fin thickness

n_f is the number of fins

Reynolds correction factor, C_2:

$$C_2 = 0.07 + 8 \cdot Re - 0.45$$

$$R_e = \frac{G_n \cdot d_o}{12 \cdot \mu_b}$$

μ_b is the gas dynamic viscosity

Geometry correction

C_4: For segmented fin tubes arranged in, for an inline pattern,

$$C_4 = 0.80 \cdot \left(0.15 \cdot \frac{P_t}{d_o}\right) \cdot \left[-1.1 \cdot \left(\frac{l_f}{s_f}\right)^{0.20}\right]$$

where

l_f is the fin height

s_f is the fin spacing

Non-equilateral & row correction

C6: For fin tubes arranged in, an inline pattern,

$$C_6 = 1.6 + \left[0.75 - 1.5 \cdot e^{(-0.70 \cdot N_r)}\right] \cdot e^{\left[-2.0 \cdot \left(\frac{P_l}{P_t}\right)^2\right]}$$

N_r is the number of tube rows

P_l is the longitudinal tube pitch

P_t is the transverse tube pitch

$P_l := 0.176 \cdot m$

$P_t = 0.203\,m$

$N_r = 4$

$$C_6 := 1.6 + \left[0.75 - 1.5 \cdot e^{(-0.70 \cdot N_r)}\right] \cdot e^{\left[-2.0 \cdot \left(\frac{P_l}{P_t}\right)^2\right]} \qquad C_6 = 1.747$$

$l_f := 0.019 \cdot m$

$s_f := 0.0013 \cdot m$

$$C_4 := 0.80 \cdot \left(0.15 \cdot \frac{P_t}{d_o}\right) \cdot \left[1.1 \cdot \left(\frac{l_f}{s_f}\right)^{0.20}\right] \qquad C_4 = 0.402$$

$$R_e := \frac{G_n \cdot d_o}{12 \cdot \mu_b} \qquad R_e = 17913.813$$

$$C_2 := 0.07 + 8 \cdot Re - 0.45 \qquad C_2 = 2.53 \times 10^8$$

$t_f := 0.0127$

$n_f := 4$

$$A_c := \frac{(d_o + 2 \cdot l_f \cdot t_f \cdot n_f)}{12} \qquad A_c = 0.01\,m$$

$$A_n := A_d - A_c \cdot L_e \cdot N_t \qquad A_n = 0.23\,m^2$$

$$A_d := \left(\frac{N_t \cdot P_t}{12}\right) \cdot L_e \qquad A_d = 0.536\,m^2$$

$$B := \frac{A_n}{A_d} \qquad B = 0.429$$

$$\rho_b := 0.394 \cdot \frac{kg}{m^3}$$

$$\rho_{in} := 0.327 \cdot \frac{kg}{m^3}$$

$$\rho_{out} := 0.497 \cdot \frac{kg}{m^3}$$

$$a := -\left[\frac{\left(1 + B^2\right)}{\left(4 \cdot N_r\right)}\right] \cdot \rho_b \cdot \left[\left(\frac{1}{\rho_{out}}\right) - \left(\frac{1}{\rho_{in}}\right)\right]$$

$$a = 0.03$$

$$d_f := 0.0127 \cdot m$$

$$f := C_2 \cdot C_4 \cdot C_6 \cdot \left(\frac{d_f}{d_9}\right)$$

$$f = 1.979 \times 10^7$$

$$\Delta P := \frac{\left[(f + a) \cdot G_n{}^2 \cdot N_r\right]}{\rho_b \cdot 1.083 \cdot 10^9}$$

$$\Delta P = 16.501 \frac{N}{m^2}$$

Stud Tube Pressure Loss:

For the stud tube pressure loss, the Muhlenforth method will be used. The general equation for staggered or inline tubes is given as,

$$\Delta P = N_r \cdot 0.0514 \cdot n_s \cdot \left[\frac{\left(C_{min} - d_o - 0.8 \cdot l_s\right)}{\left[n_s \cdot \left(C_{min} - d_o - 1.2 \cdot l_s\right)^2\right]^{0.555}}\right]^{1.8} \cdot G_s \cdot \left(\frac{T_g}{1460}\right)$$

where,

ΔP is the pressure drop across tubes

N_r is the number of tube rows

C_{min} is the minimum tube space, diagonal or transverse

d_o outside tube diameter

l_s is the length of stud

G is the mass gass velocity

T_g is the average gas Temperature

Correction for inline tubes

$$\Delta P = \Delta P \cdot \left[\left(\frac{d_o}{C_{min}}\right)^{0.333}\right]^2$$

$$G = \frac{Wg}{\left(A_n \cdot 3600\right)}$$

$$A_n = L_e \cdot N_t \cdot \frac{\left[P_t - d_o - \frac{\left(l_s \cdot r_s \cdot r_s\right)}{12}\right]}{12}$$

where,

W_g is the mass flow of gas

A_n is the net free area of tubes

L_e is the length of tubes

N_t is the number of tubes wide

P_t is the transverse tube pitch

l_s is the length of stud

t_s is the diameter of stud

r_s is the rows of studs

$l_s := 0.0127 \cdot m$

$r_s := 4$

$t_s := 0.0127 \cdot m$

$P_t = 0.203\,m$

$d_o = 0.114\,m$

$$A_n := L_e \cdot N_t \cdot \frac{\left[P_t - d_o - \frac{\left(l_s \cdot t_s \cdot r_s\right)}{12 \cdot m}\right]}{12}$$

$A_n = 0.235\,m^2$

$$G := \frac{W_g}{(A_n \cdot 3600)}$$

$$G = 0.003 \frac{kg}{m^2 \cdot s}$$

Assuming that the tube space is $C_{min} := 50 \cdot mm$

$$\Delta P := \Delta P \cdot \left[\left(\frac{d_o}{C_{min}}\right)^{0.333}\right]^2$$

$$\Delta P = 28.569 \frac{N}{m^2}$$

PRESSURE LOSS ACROSS STACK ENTRY

This pressure loss can normally be considered as a sudden entry since the area of the outlet gas plenum in the heater is usually much greater than the area of the inlet to the transition. A sudden entry pressure loss can be approximated by the following equation.

$$\Delta P = 0.34 \cdot V_h$$

ΔP is the pressure drop

V_h is the velocity head at inlet area

PRESSURE LOSS ACROSS DAMPER

This pressure loss is normally accounted for by rule of thumb. This may be 0.5 or 0.25 velocity

head. Assuming 0.25.

$$\Delta P = 0.25 \cdot V_h$$

where

ΔP is the pressure drop

V_h is the average velocity head of stack

Stack friction loss:

For the stack friction loss, we can use the following equation.

$$\Delta P = \frac{(0.002989 \cdot 0.018 \cdot r_g \cdot V_g^2)}{D_s \cdot L_s}$$

where

ΔP is the pressure drop

V_g is the average velocity of stack

r_g is the density of flue gas

D_s is the stack diameter

L_s is the stack length

Stack draft gain:

The draft gain will be taken based on the height, "A" on above sketch.

$$G_d = \frac{(\rho_a - \rho_g)}{5.2} \cdot H_g$$

where

G_d is the draft gain

ρ_g is the density of flue gas

ρ_a is the density of ambient air

H_g = Height of gas path

Pressure loss across stack exit:

This pressure loss, since it normally exits to atmosphere, can be considered as a sudden exit. A

sudden exit pressure loss can be approximated by the following equation.

$$\Delta P = 10 \cdot V_h$$

where

ΔP is the pressure drop

V_h is the velocity head at inlet area

Velocity head of gas:

$$V_h = V_g^{\,2} \cdot \frac{\rho_g}{2 \cdot 32.2 \cdot 144} \cdot 27.67783$$

Now, calculating,

$$V_g := 2.365 \cdot \frac{kg}{s}$$

$$V_h := V_g^2 \cdot \frac{\rho_g}{2 \cdot 32.2 \cdot 144 \cdot \frac{kg^2}{m^2}} \cdot 27.67783 \qquad V_h = 0.005 \frac{N}{m^2}$$

$$\Delta P := 10 \cdot V_h \qquad \Delta P = 0.051 \frac{N}{m^2}$$

$$\rho_a := 1.216 \cdot \frac{kg}{m^3}$$

$$H_g := 0.914 \cdot m$$

$$G_d := \frac{(\rho_a - \rho_g)}{5.2} \cdot H_g \qquad G_d = 0.16\, kg\, m^{-2}$$

$$D_s := 0.863 \cdot m$$

$$L_s := 6.325 \cdot m$$

$$\Delta P := \frac{\left(0.002989 \cdot 0.018 \cdot \rho_g \cdot V_g^2\right)}{D_s \cdot L_s} \qquad \Delta P = 1.698 \times 10^{-5} kg^2 m^{-4} \frac{N}{m^2}$$

Ducting Pressure Losses

Furnace designers utilize ducting for many purposes in a fired heater design. They are used for connecting flue gas plenums to stacks, distributing combustion air to burners, transfering flue gas to and from air preheat systems, etc. The pressure losses through ducting pieces may be individually analyzed or the may be analyzed as a system.

Straight duct run friction loss:

$$\Delta P = \left(0.002989 \cdot F_r \cdot r_g \cdot V_g^2\right) \cdot \frac{L_e}{D_e}$$

where,

ΔP is the pressure drop

F_r is the Moody friction factor

r_g is the average gas density

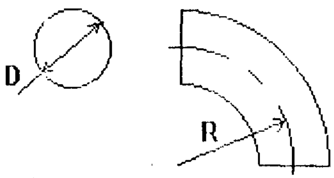
V_g is the velocity of gas

L_e is the equivalent length of piece

D_e is the equivalent diameter of piece

For round duct, $D_e = \text{diameter}$

90° Round section elbow loss:



$$\Delta P = V_h \cdot C_l$$

where

V_h is the velocity head of gas

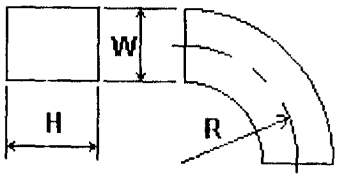
C_l is the loss coefficient

For $C_l := 0.33$

$$\Delta P := V_h \cdot C_l$$

$$\Delta P = 0.002 \frac{N}{m^2}$$

90° Rectangular section elbow loss:



$$\Delta P = V_h \cdot C_l$$

where

V_h is the velocity head of gas

C_l is the loss coefficient

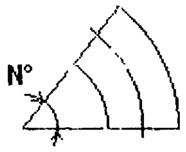
For $C_l := 0.37$

$$\Delta P := V_h \cdot C_l$$

$$\Delta P = 0.002 \frac{N}{m^2}$$

Elbow of any degree turn loss:

This may be used for a rectangular or round duct elbow of N ° turn.



$$\Delta P = V_h \cdot C_{90} \cdot \frac{N}{90}$$

where

V_h is the velocity head of gas

C_{90} is the loss coefficient from above for 90° turn

N is the number of degrees of turn

Given that,

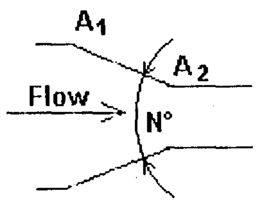
$C_{90} := 0.25$

$N' := 90$

$$\Delta P := V_h \cdot C_{90} \cdot \frac{N'}{90}$$

$$\Delta P = 0.001 \frac{N}{m^2}$$

Gradual contraction loss:



$$\Delta P = V_h \cdot C_l$$

where

V_h is the velocity head of gas

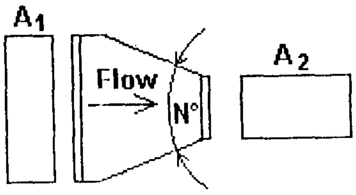
C_l is the loss coefficient

Given that,

$C_l := 0.04$

$\Delta P := V_h \cdot C_l$ $\Delta P = 0\,\frac{N}{m^2}$

No contraction change of axis loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

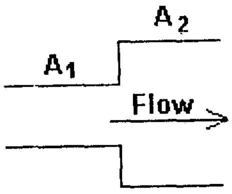
C_l is the loss coefficient

Given that,

$C_l := 0.15$

$\Delta P := V_h \cdot C_l$ $\Delta P = 0.001\,\frac{N}{m^2}$

Sudden enlargement loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

C_l is the loss coefficient

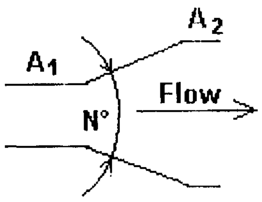
Given that,

$C_l := 0.49$

$\Delta P := V_h \cdot C_l$

$\Delta P = 0.003 \frac{N}{m^2}$

Gradual enlargement loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

C_l is the loss coefficient

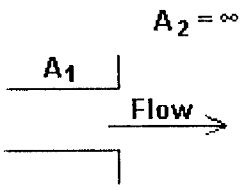
Given that,

$C_l := 0.59$

$\Delta P := V_h \cdot C_l$

$\Delta P = 0.003 \frac{N}{m^2}$

Sudden exit loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

C_l is the loss coefficient

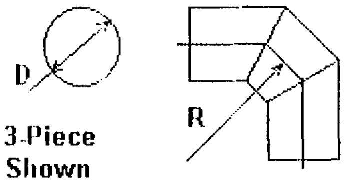
Given that,

$C_l := 1.0$

$\Delta P := V_h \cdot C_l$

$\Delta P = 0.005 \frac{N}{m^2}$

90° Round miter elbow loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

C_l is the loss coefficient

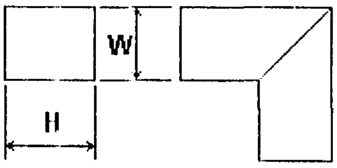
Given that,

$C_l := 0.47$

$\Delta P := V_h \cdot C_l$

$$\Delta P = 0.002 \frac{N}{m^2}$$

90° Rectangular miter elbow loss:



$\Delta P = V_h \cdot C_l$

where

V_h is the velocity head of gas

C_l is the loss coefficient

Given that,

$C_l := 1.5$

$\Delta P := V_h \cdot C_l$

$$\Delta P = 0.008 \frac{N}{m^2}$$

TUBE WALL TEMPERATURE CALCULATION

The temperature of the tube wall may be calculated using the following equations. This method does not take coking into account.

$$T_w = \text{Flux} \cdot \frac{d_o}{d_i} \cdot R_{fi} + \text{Flux} \cdot \frac{d_o}{d_i} \cdot \frac{1}{h_i} + \text{flux} \cdot \frac{d_o}{(d_o - t_w) \cdot \frac{t_w}{(k_w \cdot 12)}} + T_f$$

where

T_w is the tube wall temperature

Flux is the flux rateof bare tube

d_0 is the outside tube diameter

d_i is the inside tube diameter

t_w is the tube wall thickness

R_{fi} is the inside fouling factor

h_i is the fluid film coefficient

k_w is the thermal conductivity of tube wall

T_f is the bulk process fluid temperature

$$\text{Flux} := 1.136 \times 10^5 \cdot \frac{\text{kJ}}{\text{hr} \cdot \text{m}^2}$$

$$R_{fi} := 4.892 \times 10^{-5} \cdot \frac{\text{hr} \cdot \text{m}^2 \cdot \text{K}}{\text{kJ}}$$

$$h_i := 1.635 \times 10^4 \cdot \frac{\text{kJ}}{\text{hr} \cdot \text{m}^2 \cdot \text{K}}$$

$$T_{di} := 0.102 \cdot \text{m}$$

$$T_{do} := 0.114 \cdot \text{m}$$

$$t_w := T_{do} - T_{di}$$

$$k_w := 155.766 \cdot \frac{\text{kJ}}{\text{hr} \cdot \text{m} \cdot \text{K}}$$

$T_f := 533 \cdot K$

$$T_w := Flux \cdot \frac{d_o}{d_i} \cdot R_{fi} + Flux \cdot \frac{d_o}{d_i} \cdot \frac{1}{h_i} + Flux \cdot \frac{d_o}{(d_o - t_w)} \cdot \frac{t_w}{(k_w \cdot 12)} + T_f$$

$T_w = 543.133\ K$

The minimum volume of the furnace can be calculated with the knowledge of the mass and densityof the materials inside it. Therefore, if the densities of the components, having given the mass before as

$$m_{in} = \begin{pmatrix} 18143.69 \\ 0 \\ 515.66 \\ 0 \\ 0 \end{pmatrix} \frac{kg}{hr}$$

The volume occupied by each material can thus be calculated as

$$Vol := \sum \overrightarrow{\frac{m_{in}}{\rho}}$$

$Vol = 6.422 \frac{m^3}{hr}$

The minimum volume of the furnace is thus equal to

$V_{furnace} := Vol$

$V_{furnace} = 6.422 \frac{m^3}{hr}$

In order to estimate the diameter, height and area of the furnace tube, an assumption

that the tube is cylindrical will be made.

If the tube of the furnace is assumed to be cylindrical, its volume is given as

$V = \pi \cdot R^2 \cdot H$

and, since

$$R = \frac{D}{2}$$

$$V = \pi \cdot \left(\frac{D}{2}\right)^2 \cdot h$$

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

Assming that H= kD, where k is a constant substituting for H yields,

$$V = \pi \cdot \frac{D^2}{4} \cdot (k \cdot D)$$

$$4 \cdot V = k \cdot \pi \cdot D^3$$

Making d the subject of the formular

$$D = \left(\frac{4 \cdot V}{k \cdot \pi}\right)^{\frac{1}{3}}$$

For a standard tube, $k := 2$

$$V_{furnace} := V_{furnace} \cdot hr$$

$$D_{furnace} := \left(\frac{4 \cdot V_{furnace}}{k \cdot \pi}\right)^{\frac{1}{3}} \qquad D_{furnace} = 1.599\,m$$

From

$$H_{furnace} := k \cdot D_{furnace}$$

$$H_{furnace} = 3.198\,m$$

The area of the furnace is therefore,

$$A_{furnace} := 2\pi \cdot \frac{D_{furnace}}{2} \cdot H_{furnace} + 2\pi \cdot \left(\frac{D_{furnace}}{2}\right)^2 \qquad A_{furnace} = 20.08\,m^2$$

6.1.6 DESIGN OF COOLER

Coolers play an essential role in chemical processing. They are services in which heat is transferred from a hot material to cold material which actually occurs as a result of temperature difference between the two streams. This method is used in proper process plants to bring the feed to the required specified state of the reaction before it enters the reactor.

SPECIFICATIONS

Heat capacity coefficients:

$$\text{Data} := \begin{pmatrix} 82.34 & 4.975\cdot 10^{-2} & -12.87\cdot 10^{10}\cdot 10^{-5} & 0 \\ 18.2964 & 47.212\cdot 10^{-2} & -133.88\cdot 10^{-5} & 1314.2\cdot 10^{-9} \\ 15.2 & 2.68\cdot 10^{-2} & 0 & 0 \\ 41.84 & 2.03\cdot 10^{-2} & -4.52\cdot 10^{10}\cdot 10^{-5} & 0 \\ 36.11 & 4.233\cdot 10^{-2} & -2.887\cdot 10^{-5} & 7.464\cdot 10^{-9} \end{pmatrix} \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix}$$

$$\begin{pmatrix} CaCO_3 \\ H_2O \\ \text{Impurities} \\ CaO \\ CO_2 \end{pmatrix} \qquad mw := \begin{pmatrix} 100.09 \\ 18.016 \\ 60.00 \\ 56.08 \\ 44.01 \end{pmatrix}\cdot\frac{kg}{kmol} \qquad m' := \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 10160.47 \\ 0.00 \end{pmatrix}\cdot\frac{kg}{hr}$$

$T_{in} := (1000 + 273)\cdot K$ $\qquad$ $T_{out} := (100 + 273)\cdot K$

$T_b := \dfrac{T_{in} + T_{out}}{2}$ $\qquad$ $T_b = 823\,K$

At this temperature, the specific capacity of fatty acids product is given as

$a_b := Data_{1,1}$ $\qquad$ $b_b := Data_{1,2}$ $\qquad$ $c_b := Data_{1,3}$ $\qquad$ $d_b := Data_{1,4}$

$a_b = 82.34$ $\qquad$ $b_b = 0.05$ $\qquad$ $c_b = -1.287\times 10^{6}$ $\qquad$ $d_b = 0$

$$C_p := \left[a_b + b_b\cdot\frac{T_b}{K} + c_b\cdot\left(\frac{T_b}{K}\right)^2 + d_b\cdot\left(\frac{T_b}{K}\right)^3\right]\cdot\frac{kJ}{kmol\cdot K}$$

$$C_p = -8.717\times 10^{11}\,\frac{kJ}{kmol\cdot K}$$

$n_{comp} := \sum\overrightarrow{\left(\frac{m'}{mw}\right)}$ $\qquad$ $n_{comp} = 181.178\,\dfrac{kmol}{hr}$

$Heat\_duty := n_{comp}\cdot C_p\cdot\left(T_{out} - T_{in}\right)$

$Heat\_duty = 3.948\times 10^{13}\,kW$

$Q := Heat\_duty$ $\qquad$ $Q = 3.948\times 10^{13}\,kW$

As a trial, the mean temperature of the water is taken to be equal to the inlet temperature, 100°C; specific heat capacity at this temperature is

$a_w := Data_{3,1}$ $b_w := Data_{3,2}$ $c_w := Data_{3,3}$ $d_w := Data_{3,4}$

$a_w = 15.2$ $b_w = 0.027$ $c_w = 0$ $d_w = 0$

$T_w := (35 + 273) \cdot K$

$$c_{pw} := \left[a_w + b_w \cdot \frac{T_w}{K} + c_w \cdot \left(\frac{T_w}{K}\right)^2 + d_w \cdot \left(\frac{T_w}{K}\right)^3\right] \cdot \frac{kJ}{kg \cdot K} \qquad c_{pw} = 23.454 \, \frac{kJ}{kg \cdot K}$$

PHYSICAL PROPERTIES:

LIME

Heat capacities of the lime at the inlet, outlet and mean condition:

$T_{bi} := T_{in}$ $T_{bo} := T_{out}$ $T_{bm} := T_b$

$$c_{pbi} := \left[a_b + b_b \cdot \frac{T_{bi}}{K} + c_b \cdot \left(\frac{T_{bi}}{K}\right)^2 + d_b \cdot \left(\frac{T_{bi}}{K}\right)^3\right] \cdot \frac{kJ}{kmol \cdot K} \qquad c_{pbi} = -2.086 \times 10^{12} \, \frac{kJ}{kmol \cdot K}$$

$$c_{pbo} := \left[a_b + b_b \cdot \frac{T_{bo}}{K} + c_b \cdot \left(\frac{T_{bo}}{K}\right)^2 + d_b \cdot \left(\frac{T_{bo}}{K}\right)^3\right] \cdot \frac{kJ}{kmol \cdot K} \qquad c_{pbo} = -1.791 \times 10^{11} \, \frac{kJ}{kmol \cdot K}$$

$$c_{pbm} := \left[a_b + b_b \cdot \frac{T_{bm}}{K} + c_b \cdot \left(\frac{T_{bm}}{K}\right)^2 + d_b \cdot \left(\frac{T_{bm}}{K}\right)^3\right] \cdot \frac{kJ}{kmol \cdot K} \qquad c_{pbm} = -8.717 \times 10^{11} \, \frac{kJ}{kmol \cdot K}$$

Therefore, the properties of fatty acids at the inlet, outlet and mean conditions are

$$\begin{pmatrix} \text{Inlet} \\ \text{Mean} \\ \text{Outlet} \end{pmatrix} \qquad T_{comp} := \begin{pmatrix} T_{bi} \\ T_{bm} \\ T_{bo} \end{pmatrix} \qquad c_{p\_comp} := \begin{pmatrix} c_{pbi} \\ c_{pbm} \\ c_{pbo} \end{pmatrix} \qquad k_{comp} := \begin{pmatrix} 0.0413 \\ 0.0324 \\ 0.0355 \end{pmatrix} \cdot \frac{W}{m \cdot K}$$

$$\rho_{comp} := \begin{pmatrix} 840 \\ 844 \\ 846 \end{pmatrix} \cdot \frac{kg}{m^3} \qquad \mu_{comp} := \begin{pmatrix} 9.707 \\ 10.233 \\ 10.003 \end{pmatrix} \cdot mN \cdot s \cdot m^{-2}$$

WATER

Heat capacities of the water at the inlet, outlet and mean condition:

$$T_{wi} := (35 + 273) \cdot K \qquad T_{wo} := (90 + 273) \cdot K \qquad T_{wm} := \frac{T_{wi} + T_{wo}}{2}$$

$$c_{pwi} := \left[a_w + b_w \cdot \frac{T_{wi}}{K} + c_w \cdot \left(\frac{T_{wi}}{K}\right)^2 + d_w \cdot \left(\frac{T_{wi}}{K}\right)^3 \right] \cdot \frac{kJ}{kg \cdot K}$$

$$c_{pwi} = 23.454 \frac{kJ}{kg \cdot K}$$

$$c_{pwo} := \left[a_w + b_w \cdot \frac{T_{wo}}{K} + c_w \cdot \left(\frac{T_{wo}}{K}\right)^2 + d_w \cdot \left(\frac{T_{wo}}{K}\right)^3 \right] \cdot \frac{kJ}{kg \cdot K}$$

$$c_{pwo} = 24.928 \frac{kJ}{kg \cdot K}$$

$$c_{pwm} := \left[a_w + b_w \cdot \frac{T_{wm}}{K} + c_w \cdot \left(\frac{T_{wm}}{K}\right)^2 + d_w \cdot \left(\frac{T_{wm}}{K}\right)^3 \right] \cdot \frac{kJ}{kg \cdot K}$$

$$c_{pwm} = 24.191 \frac{kJ}{kg \cdot K}$$

In summary, the properties of water at the inlet, outlet and mean conditions are

$$T_{water} := \begin{pmatrix} T_{wi} \\ T_{wm} \\ T_{wo} \end{pmatrix} \qquad c_{p\_water} := \begin{pmatrix} c_{pw} \\ c_{pwm} \\ c_{pwo} \end{pmatrix} \qquad k_{water} := \begin{pmatrix} 0.59 \\ 0.60 \\ 0.61 \end{pmatrix} \cdot \frac{W}{m \cdot K}$$

$$\rho_{water} := \begin{pmatrix} 980 \\ 990 \\ 1000 \end{pmatrix} \cdot \frac{kg}{m^3} \qquad \mu_{water} := \begin{pmatrix} 0.8 \\ 0.85 \\ 0.9 \end{pmatrix} \cdot 10^{-3} \cdot N \cdot s \cdot m^{-2}$$

OVERALL COEFFICIENT

For a cooler of this type, the overall coefficient will be in the range 300 to 500 W/m^{2}oC, Figure 12.1 and Table 12.1 (Richardson and Coulson); taking $U := 380 \cdot \frac{W}{m^2 \cdot K}$

COOLER TYPE AND DIMENSIONS

An even number of tube passes is usually the preferred arrangement, as this positions the inlet and outlet nozzles at the same end of the exchanger, which simplifies the pipework. Starting with one shell pass and 2 tube passes,

$$\Delta T_{lm} := \left| \frac{\left(T_{water_1} - T_{comp_1}\right) - \left(T_{water_3} - T_{comp_3}\right)}{\ln\left[\frac{\left(T_{water_1} - T_{comp_1}\right)}{\left(T_{water_3} - T_{comp_3}\right)}\right]} \right| \qquad \Delta T_{lm} = 208.992\,K$$

$$R := \frac{T_{water_1} - T_{water_3}}{T_{comp_3} - T_{comp_1}} \qquad R = 0.061$$

$$S := \frac{T_{comp_3} - T_{comp_1}}{T_{water_1} - T_{comp_1}} \qquad S = 0.933$$

From Figure 12.19, $F_t := 7 \cdot 10^9$, which is acceptable.

So, $\Delta T_m := F_t \cdot \Delta T_{lm}$ $\qquad \Delta T_m = 1.463 \times 10^{12}\,K$

HEAT TRANSFER AREA

From the formula given as

$$Q = U \cdot A \cdot \Delta T_m$$

$$A_{cooler} := \frac{|Q|}{U \cdot \Delta T_m} \qquad A_{cooler} = 71.025\,m^2$$

LAYOUT AND TUBE SIZE

Using a split-ring floating head exchanger for efficiency and ease of cleaning.

Neither material is corrosive, and the operating pressure is not high, so a plain carbon steel can be used for the shell and tubes.

Using 19.05 mm (3/4 inch) outside diameter (i..e, $D_o := 19.05mm$), 14.83 mm inside diameter (i.e. $D_i := 14.83mm$), 5 m long tubes (i.e. $L := 5m$) (a popular size) on a triangular 23.81 mm (i.e. $p_t := 23.81 \cdot mm$) pitch (pitch/dia. = 1.25).

NUMBER OF TUBES

Area of one tube (neglecting thickness of tube sheets) is given thus;

$$A_{one\_tube} := \pi \cdot D_o \cdot L \qquad A_{one\_tube} = 0.299\,m^2$$

Number of tubes

$$N_t := \frac{A_{cooler}}{A_{one\_tube}} \qquad N_t = 237.35$$

So, for two passes, tubes per pass is

$$tube\_per\_pass := \frac{N_t}{2} \qquad tube\_per\_pass = 118.677$$

Check the tube-side velocity at this stage to see if it looks reasonable.

$$A_{tube} := \frac{\pi}{4} \cdot \left(D_i^{\,2}\right) \qquad A_{tube} = 0.0001727\,m^2$$

So,

$$area\_per\_pass := tube\_per\_pass \cdot A_{tube} \qquad area\_per\_pass = 0.02\,m^2$$

$$m_{water} := 85000 \cdot \frac{kg}{hr}$$

$$Volumetric\_flow_t := m_{water} \cdot \frac{1}{\rho_{water_2}} \qquad Volumetric\_flow_t = 85.859\,\frac{m^3}{hr}$$

Tube side velocity, $u_t := \frac{Volumetric\_flow_t}{area\_per\_pass}$

$$u_t = 1.163\,\frac{m}{s}$$

The velocity is satisfactory but this will show up when the pressure drop is calculated.

BUNDLE AND SHELL DIAMETER

From Table 12.4, for 2 passes, $K_1 := 0.249$, $n_1 := 2.207$

$$D_b := D_o \cdot \left(\frac{N_t}{K_1}\right)^{\frac{1}{n_1}} \qquad D_b = 0.426\,m$$

For a split-ring floating head exchanger the typical shell clearance from Figure 12.10 (Richardson and Coulson) is 56 mm (i.e. $S_c := 56 \cdot mm$), so the shell inside diameter,

$$D_s := D_b + S_c \qquad D_s = 0.482\,m$$

TUBE-SIDE HEAT TRANSFER COEFFICIENT

$$Re = \frac{G_s \cdot d_e}{\mu} = \frac{u_s \cdot d_e \cdot \rho}{\mu}$$

$$Re := \frac{\rho_{water_2} \cdot u_t \cdot D_i}{\mu_{water_2}} \qquad Re = 20095.533$$

$$P_r = \frac{c_p \cdot \mu}{k}$$

$$P_r := \frac{c_{p\_water_2} \cdot \mu_{water_2}}{k_{water_2}} \qquad P_r = 34.271$$

$$\frac{L}{D_i} = 337.154 \qquad \mu := 0.99 N \cdot m \cdot s^{-2}$$

$$\mu_w := 1 \cdot \left(N \cdot m \cdot s^{-2}\right)$$

From figure 12.23 (Richardson and Coulson). $j_h := 3.2 \cdot 10^{-3}$

$$Nu := j_h \cdot Re \cdot P_r^{\frac{1}{3}} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad Nu = 208.584$$

$$h_i := Nu \cdot \left(\frac{k_{water_2}}{D_i}\right) \qquad h_i = 8439.009 \frac{W}{m^2 \cdot K}$$

This is clearly too low if U_0 is to be 370 W/m^2oC. The tube-side valocity did look low, so the number of tube passes will be increased to 4. This will have the cross-sectional area in each pass and double the velocity.

$$u_t := 2 \cdot u_t \qquad u_t = 2.327 \frac{m}{s}$$

$$Re := 2 \cdot Re \qquad Re = 40191.067$$

$$j_h := 3.8 \cdot 10^{-3}$$

$$Nu := j_h \cdot Re \cdot P_r^{\frac{1}{3}} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad Nu = 495.387$$

$$h_i := Nu \cdot \left(\frac{k_{water_2}}{D_i}\right) \qquad h_i = 20042.646 \frac{W}{m^2 \cdot K}$$

SHELL-SIDE HEAT TRANSFER COEFFICIENT

Using Kern's method,

For 4 passes, $K_1 := 0.175$ and $n_1 := 2.285$

$$D_b := D_o \cdot \left(\frac{N_t}{K_1}\right)^{\frac{1}{n_1}} \qquad D_b = 0.447\,\mathrm{m}$$

The bundle to shell clearance is still around 56 mm, giving:

$$D_s := D_b + S_c \qquad D_s = 0.503\,\mathrm{m}$$

As a first trial, the baffle spacing is taken as $l_b := \frac{D_s}{5}$. This spacing should give good heat transfer without too high a pressure drop.

$$A_s := \frac{(p_t - D_o) \cdot D_s \cdot l_b}{p_t} \qquad A_s = 0.01013\,\mathrm{m}^2$$

$$d_e := \frac{1.10}{D_o} \cdot \left(p_t^2 - 0.917 \cdot D_o^2\right) \qquad d_e = 0.01352\,\mathrm{m}$$

Volumetric flow-rate on shell-side

$$\mathrm{Volumetric\_flow}_s := \frac{n_{comp} \cdot mw_5}{\rho_{comp_2}} \qquad \mathrm{Volumetric\_flow}_s = 226.739\,\frac{\mathrm{m}^3}{\mathrm{day}}$$

Shell-side velocity

$$u_s := \frac{\mathrm{Volumetric\_flow}_s}{A_s} \qquad u_s = 0.259\,\frac{\mathrm{m}}{\mathrm{s}}$$

$$Re := \frac{\rho_{comp_2} \cdot u_s \cdot D_i}{\mu_{comp_2}} \qquad Re = 316.758$$

$$P_r := \frac{c_{p\_comp_2} \cdot \mu_{comp_2}}{k_{comp_2} \cdot mw_5} \qquad P_r = -6.256 \times 10^{12}$$

Using segmental baffles with a 25% cut. This should give a reasonable heat transfer coefficient

without too large a pressure drop.

From Figure 12.29 (Richardon and Coulson), $j_h := 4.52 \cdot 10^{-3}$.

Neglecting the viscosity correction

$$h_s := \frac{k_{comp_2}}{d_e} \cdot j_h \cdot Re \cdot P_r^{\frac{1}{3}} \qquad h_s = 31611.588 + 54752.877i \frac{W}{m^2 \cdot K}$$

$$f_{water} := 2857.14 \cdot \frac{W}{m^2 \cdot K} \qquad f_{comp} := 5000 \cdot \frac{W}{m^2 \cdot K}$$

$$U_o := \left[\left(\frac{1}{h_i} + \frac{1}{f_{water}}\right) \cdot \frac{D_o}{D_i} + \frac{D_i \cdot \ln\left(\frac{D_o}{D_i}\right)}{k_{comp_2}} + \frac{1}{h_s} + \frac{1}{f_{comp}}\right]^{-1}$$

$$U_o = 8.67 + 0.001i \frac{W}{m^2 \cdot K}$$

PRESSURE DROP

TUBE SIDE

240 tubes, 4 passes, $D_i = 0.0148\,m$, $u_t = 2.327\,m\,s^{-1}$, $Re = 316.758$. From Figure 12.24 (Richardon and Coulson), $j_f := 5 \cdot 10^{-3}$.

$$\Delta P_t := 4 \cdot 8 \cdot j_f \cdot \left(\frac{D_s}{d_e}\right) \cdot \left(\frac{L}{l_b}\right) \cdot \frac{\rho_{water_2} \cdot u_s^2}{2} \cdot \left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_t = 9835.747 \frac{N}{m^2}$$

6.2 MECHANICAL DESIGN OF EQUIPMENTS

6.2.1 MECHANICAL DESIGN OF COOLER

Working pressure, $P_w := 0.101 \cdot \frac{N}{mm^2}$

Design temperature, $T_d := 423$

Design pressure, $P_d := 0.1084 \cdot \frac{N}{mm^2}$

Number of tubes, $N_t = 237$

Shell diameter, $D := 540 \cdot mm$

1. Shell thickness

Material: IS 2825 - 1969 Grade I plain carbon steel

Shell thickness is given as

$$t_s = \frac{P \cdot D}{2 \cdot f \cdot J + P}$$

where ts is the thickness

P is the design pressure

D is the diam

f is the permissible stress

J = 0.85

Given that,

$P := P_d$

$D_i = 0.015m$

$J := 0.85$

$f := 9.5 \cdot \frac{N}{mm^2}$

$$t_s := \frac{P \cdot D_i}{2 \cdot f \cdot J + P} \qquad t_s = 0.099mm$$

It has been found from the literature that the minimum shell thickness when severe conditions are

not expected is 8mm, which includes corrosion allowance.

2. Nozzles

Taking the inlet and outled nozzles as 100mm diameter,

Vent nozzle diameter, $V_n := 25 \cdot mm$

Drain nozzle diameter, $D_n := 25 \cdot mm$

Relief valve diameter, $R_v := 50 \cdot mm$

Given that,

$P := P_d$

$D_i = 0.015 m$

$J := 0.85$

$$f := 95 \cdot \frac{N}{mm^2}$$

$$t_s := \frac{P \cdot D_i}{2 \cdot f \cdot J + P} \qquad t_s = 0.099 mm$$

Minimum nozzle thickness is 6mm and 8mm is chosen which includes the corrosion allowance.

Also, only the inlet and outlet nozzles need compensation. The compensation required is minimum

and is given by pads of 10mm thickness

Heads

Torispherical heads are taken for both ends.

Crown radius, $R_c := 540 \cdot mm$

Knuckle radius, $R_{nk} := 54 \cdot mm$

Head thickness, $t_h = \frac{P \cdot R_c \cdot W'}{2 \cdot f \cdot J}$

where

$$W' := \frac{1}{4} \cdot \left[3 + \left(\frac{R_c}{R_{nk}} \right)^{0.5} \right] \qquad W' = 1.541$$

Head thickness is therefore given as

$$t_h := \frac{P \cdot R_c \cdot W'}{2 \cdot f \cdot J} \qquad t_h = 5.584\,mm$$

Therefore, the head thickness is taken as that of the shell thickness, that is, 8mm.

4. *Transverse Baffles*

Number of baffles, $N_b := 1$

Baffle cut, $B_c := 25\%$

Baffle thickness, $B_t := 6 \cdot mm$ (standard)

5. *The Rods and Spacers*

Diameter of the rods, $D_r := 10 \cdot mm$

Diameters of spacers, $D_s := 8 \cdot mm$

6. *Flange Design*

Flange is a ring type with plain face.

Design pressure, $P_d = 0.108 \frac{N}{mm^2}$

Flange material: IS 2004 - 1962 Class 2 Carbon Steel

Bolting steel: 5% Chromium, Molybdenum Steel

Gasket material: Asbestos

Shell OD $D = 0.54\,m$

Shell thickness, $t_s = 9.888 \times 10^{-5}\,m$

Shell ID, $D_i := D - t_s$

$$D_i = 0.54\,m$$

Allowable stress for flange material, $\sigma_{flange} := 100 \cdot \frac{N}{mm^2}$

Allowable stress of bolting material, $\sigma_{bolting} := 138 \cdot \frac{N}{mm^2}$

6(i) Determination of Gasket Width

$$\frac{d_o}{d_i} = \left[\frac{(y - P \cdot m)}{y - P \cdot (m + 1)}\right]^{0.5}$$

Assume a gasket thickness of 1.6mm

Minimum design yield stress, $y := 25.5 \frac{N}{mm^2}$

Gasket factor, $m' := 2.75$

$$do\_di := \left[\frac{(y - P \cdot m')}{y - P \cdot (m' + 1)}\right]^{0.5}$$

$do\_di = 1.002$

Let $d_i := 0.550 \cdot m$

Minimum gasket width, $N_m := d_i \cdot \frac{(do\_di - 1)}{2}$ $N_m = 0.593\,mm$

Choosing $N_m := 40 \cdot mm$

$d_o := 0.630 \cdot m$ $d_o = 0.63\,m$

Basic gasket seating width, $b_o := \frac{N_m}{2}$ $b_o = 0.02\,m$

Effective gasket seating width, $b := 2.5 \cdot \left(\frac{b_o}{mm}\right)^{0.5} \cdot mm$ $b = 11.18\,mm$

Diameter of location of gasket load reaction is $G' := d_i + N_m$

$G' = 0.59\,m$

6(ii) Estimation of bolt loadsy

Under atmospheric conditions, the bolt load due to gasket reaction is given by

$W_{gr} := \pi \cdot b \cdot G' \cdot y$

$W_{gr} = 528.442\,kN$

Load due to design pressure

$L_p := \pi \cdot \frac{G'^2 \cdot P}{4}$ $L_p = 29.636\,kN$

Load to keep joint right under operation

$$L_j := \pi \cdot G' \cdot (2 \cdot b) \cdot m' \cdot P_d$$

$$L_j = 12.355\,\mathrm{kN}$$

Total operating load, $L_{total} := L_p + L_j$

$$L_{total} = 41.991\,\mathrm{kN}$$

6(iii) Calculation of Minimum Bolting Area

Given that the allowable stress for bolting material is $S := 138 \cdot \frac{N}{mm^2}$

$$A_{bolting} := \frac{W_{gr}}{S}$$

$$A_{bolting} = 0.004\,m^2$$

6(iv) Calculation of Optimum Bolt Size

Bolts are 5% of CrMo Steel.

Number of bolts, $N_{bolts} := \frac{G'}{b_o \cdot 2.5}$

$$N_{bolts} = 12\,\text{bolts}$$

Diameter of bolts, $D_{bolts} := \left(\frac{A_{bolting}}{N_{bolts}} \cdot \frac{4}{\pi}\right)^{\frac{1}{2}}$

$$D_{bolts} = 20.327\,mm$$

7. *Flange Thickness*

Thickness of flange, $t_f = \left(G' \cdot \sqrt{\frac{P}{K \cdot f}}\right) + C$

where C is the corrosion allowance

Hydrostatic end force, $H_e := \frac{\pi}{4} \cdot G'^2 \cdot P$

$$H_e = 29.636\,\mathrm{kN}$$

$$K' = \frac{1}{\left[0.3 + \left[\left(1.5 \cdot L_{total} \cdot h_G\right) \cdot (H' \cdot G')\right]\right]}$$

where h_G is the radial distance from gasket load reaction to bolt circle given as

$$h_G = \frac{(B' - G')}{2}$$

$$B' := d_o + 2 \cdot D_{bolts} + 12 \cdot mm$$

Then,

$$h_G := \frac{(B' - G')}{2} \qquad h_G = 0.046\,m$$

So, since, $H' := L_p$ $\qquad L_{total} = 41991.42\,N$

$$K' := \frac{1}{\left[0.3 + \left[\left(1.5 \cdot \frac{L_{total}}{kN} \cdot \frac{h_G}{m}\right) \cdot \left(\frac{H'}{kN} \cdot \frac{G'}{m}\right)\right]\right]} \qquad K' = 0.019$$

The thickness (given the corrosion allowance to be $C := 10 \cdot mm$) is thus calculated as

$$t_f := \left[\left(G' \cdot \sqrt{\frac{P}{K' \cdot f}}\right) + C\right] \qquad t_f = 0.462\,m$$

CHAPTER SEVEN

7.0 REACTOR/EQUIPMENT OPTIMIZATION

7.1 OPTIMIZATION OF FURNACE

In optimizing, the first step is clearly to define the objective. That is, the criterion to be used to judge the performance of the system. In engineering design, the objective of optimizing any reactor or equipment must be an economical one. This is because for any chemical plant set up, the primary objective is to maximize profits.

a) Another "Advanced Trick" involves optimization of a fired heater. Heat is being supplied to the reboiler of a deethanizer as shown in Figure 7.1. It is required to keep the temperature at the bottom of the tower constant. The heating medium is hot oil which is being heated by a fired heater and circulated by a pair of pumps. Since the tower bottoms is being boiled, and is also very clean, it goes on the shell side. The oil goes through the tube side where the outlet is throttled by a butterfly valve. A position transmitter has been added to the valve. Its output goes to a Position Controller with a set point of about 80% open. The output of the Position Controller is cascaded to the set point of the Temperature Controller of the furnace.

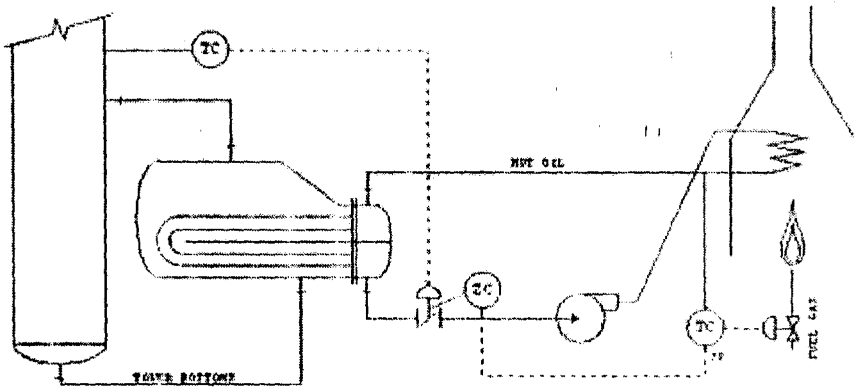


Fig. 7.1: Optimization of furnace (www.driedger.ca/ce3_stx/CE3_STX.html)

CHAPTER EIGHT

8.0 SAFETY AND QUALITY CONTROL

8.1 Safety

Safety is the area of engineering and public health which deals with the protection of workers' health, through control of the work environment to reduce or eliminate hazards. Industrial accidents and unsafe working conditions can result in temporary or permanent injury, illness, or even death. They also take a toll in reduced efficiency and loss of productivity. (Encarta, 2004)

8.1.1 General Safety Rules

Follow relevant instructions

a) Before attempting to operate the lime plant, all relevant manufacturers' instructions and local regulations should be understood and implemented.

b) It is irresponsible and dangerous to misuse equipment or ignore instructions, regulations or warnings.

c) The specified maximum operating conditions must not exceeded. (Odigure, 1998)

Operation

a) It must be ensured that all staff must be fully aware of the potential hazards when the lime plant is being operated.

b) Serious injury can result from touching apparently stationary equipment or rotating belt.

c) No metallic object should be allowed into the lime plant. Otherwise, the gear motor of the affected conveyor must be set in the reverse direction and the entrained materials should be discharged. (Odigure, 1998)

Maintenance

a) A badly maintained lime plant is a potential hazard. It must be ensured that competent members of staff is responsible for organizing maintenance and repairs on a planned basis.

b) Faulty equipment must be permitted to be operated. Repairs must be carried out competently and the operation must be checked. (Odigure, 1998)

Using electricity

a) At least once a month, the electrical cables should be checked to ensure that they are operating normally.

b) Electricity is the commonest cause of accidents in the factory, it must be respected.

c) It must be ensured that electricity supply has been disconnected from the equipment before attempting repairs or adjustment.

d) It must be known that water and electricity are not compatible and can cause serious injury if they come into contact.

e) The lime plant must always be disconnected from electricity when not in use. (Odigure, 1998)

Avoiding fire or explosion

a) It must be ensured that the factory is provided with adequate fire extinguishers appropriate to the potential dangers.

b) It must be known that empty vessels having inflammable liquids can contain vapours and explode if ignited.

Handling poisons or toxic materials

a) Food must not be allowed to be brought into or consumed in the factory.

b) Smoking should not be allowed in the factory premises. Notices should be so displayed and enforced. (Odigure, 1998)

Avoiding cuts and burns

a) Care must be taken when handling sharp edged components. Undue force must not be exerted on glass or fragile items.

b) Hot surfaces cannot, in most cases, be totally shielded and can produce severe burns even when not "visibly hot". Common sense must be used always!

Eye protection

a) Facilities for eye irritation should always be available

Ear protection

a) Ear protectors [illegible] be worn when operating the lime plant.

Guard and safety devices

a) Guards and safety devices must be installed on the lime plant to protect the operators. The equipment must not be operated with such devices removed.

b) Safety gauges, cut-out and other safety devices must be set to protect the equipment. Interference with these devices may create a potential hazard.

c) It is impossible to guard the operator against all contingencies. Common sense muse be used.

d) Before starting a machine, it must be ensured that the members of staff are aware of how it (the machine) should be stopped in an emergency. (Odigure, 1998)

First aid

a) It is essential that first aid equipment is available and that the supervisor knows how to use it.

b) A notice giving details of a proficient first aider should be prominently displayed. (Odigure, 1998)

8.2 Quality Control

Quality simply means "fitness for use". But, according to the International Standard Organisation (ISO), quality is defined as the totality of the characteristics of an entity that bear on its ability to satisfy stated and intended needs. It is more costly to exceed a specification than to meet it. Therefore, there is the need to get quality goal or target for effective quality control.

Maintaining product quality in accordance with acceptable standard has been a major role for industrial instrumentation since its inception decades ago. With the ever-increasing interest in speeding up production, one becomes aware of the fact that rejectable as well as acceptable products can be produced at high rates.

8.2.1 Quality assurance

Quality assurance is defined by ISO as all the planned and systematic activities implemented within the quality system and demonstration is needed to provide adequate confidence on entity will fulfil requirement for quality.

8.2.1.1 Principles of quality assurance

The principles of quality assurance include the following:

i. Management involvements and objective (management involvement is very essential to ensure quality.

ii. Programming and planning.

iii. Application of quality control principles.

iv. Design and specification control.

v. Purchasing control and vendor appraisal.

vi. Production control.

vii. Marketing and service quality functions.

viii. Proper documentation.

ix. Non-conformance control.

x. Remedial action.

xi. Defect and failure analysis.

8.2.1.2 Quality management

Quality management involves all activities of the overall management functions that determine the quality policy, objective and responsibilities and implement then by means, such as quality planning control assurance and improvement within the quality system. Responsibility of quality lies at all level of all. To successfully implement quality management, the organisation structure, procedure process and resources are requisite.

CHAPTER NINE

9.0 PROCESS CONTROL AND INSTRUMENTATION

It is proposed that most of the lime plant equipments in the lime plant be operated using automatic control with the indicating instruments being located in a control room. This is the general practice for a lime plant of this type which is not labour intensive. With the exception of the reactor system, the lime plant operates at atmospheric pressure and therefore the process control and instrumentation will be based upon temperature, flow and level measurements. Measurements of these parameters will be made using thermocouples, orifice plates and float type indicators respectively. (Austin & Jeffrey, 1991)

9.1 Types of control instruments

The control instruments are of four major categories

a) Temperature controllers (TC)

b) Pressure controller (PC)

c) Flow controller (FC)

d) Level controller (LC)

9.2 Process Control of Equipments

9.2.1 Process control of furnace

The purpose of a fired heater is very simple: To add heat to a process fluid. Its representation on a process flow diagram is also very simple. But, of course, fired heaters are among the most complex pieces of process control equipment. Each furnace is, after all, at least two pieces of equipment in one. Firstly, it is a special variant of the shell and tube heat exchanger since its purpose is to exchange heat.

Secondly, it is a chemical reactor in which fuel and air undergo extremely exothermic reactions to produce the required heat.

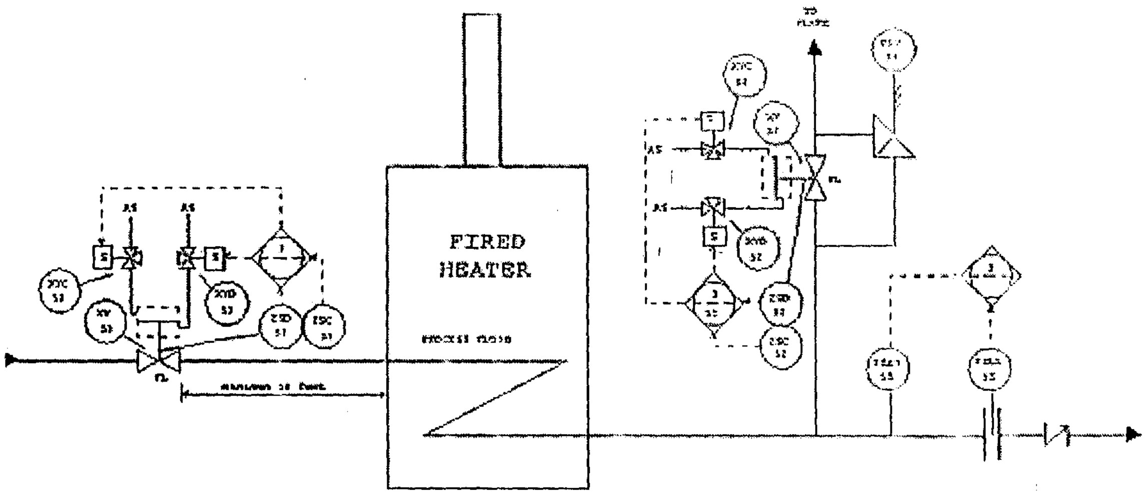
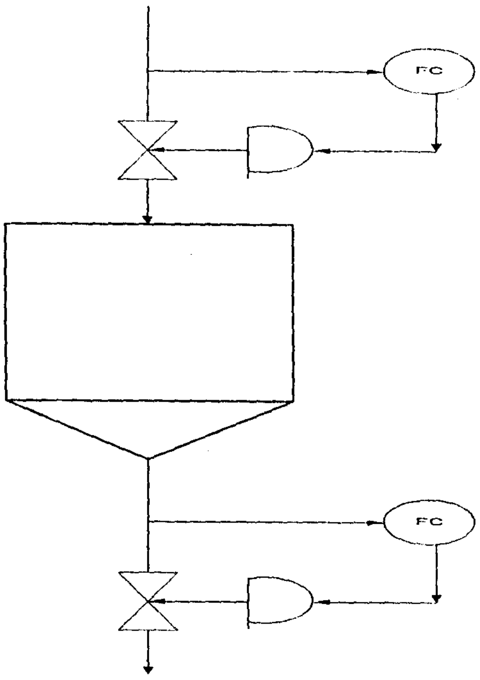
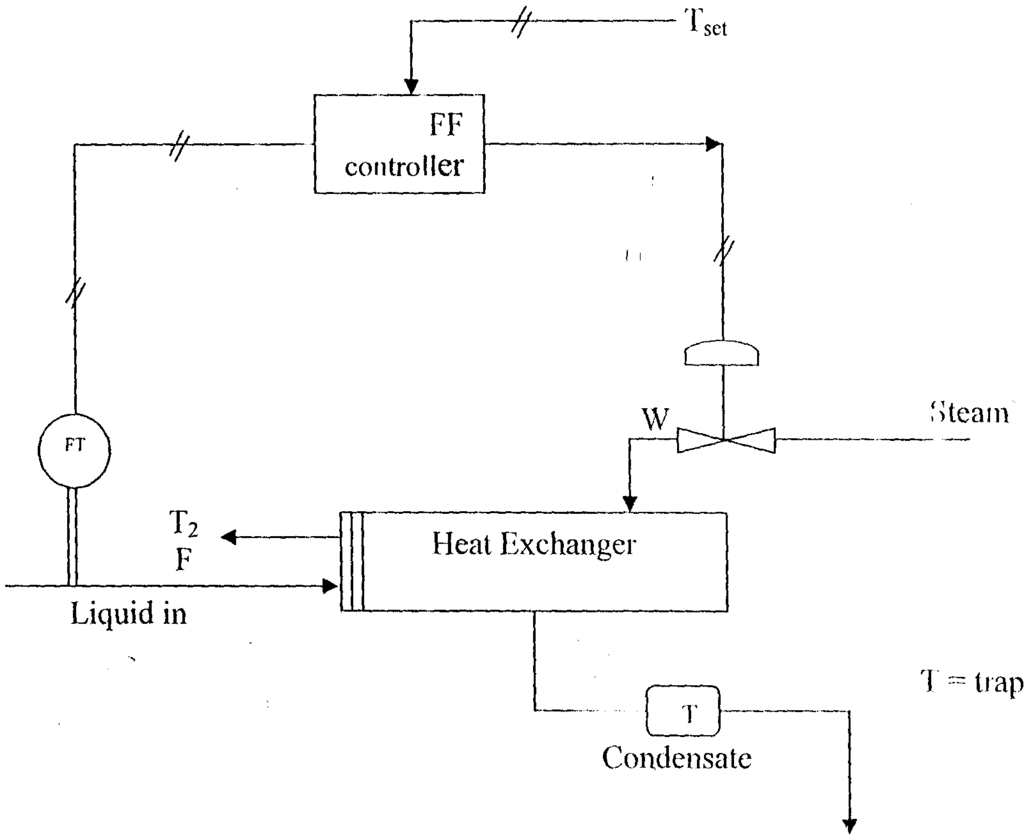


Fig. 9.1: Process control of furnace

9.2.2 *Process control of bin*



9.2.3 *Process control of cooler*



CHAPTER TEN

10.0 ENVIRONMENTAL ACCEPTABILITY

10.1 Identification of possible pollutants in lime production plant

Except for gaseous pollutants emitted from furnaces, particulate matter (PM) is the only dominant pollutant.

The largest ducted source of particulate is the furnace. The properties of the limestone feed and the ash content of the coal (in coal-fired furnaces) can significantly affect PM emission rates. Of the various furnace types, fluidized beds have the highest levels of uncontrolled PM emissions because of the very small feed rate combined with the high air flow through these furnaces. Fluidized bed furnaces are well controlled for maximum product recovery. The rotary furnace is second worst in uncontrolled PM emissions because of the small feed rate and relatively high air velocities and because of dust entrainment caused by the rotating chamber. The calcimatic (rotary hearth) furnace ranks third in dust production primarily because of the larger feed rate and the fact that, during calcination, the limestone remains stationary relative to the hearth. The vertical furnace has the lowest uncontrolled dust emissions due to the large lump feed, the relatively low air velocities, and the slow movement of material through the furnace. In coal-fired furnaces, the properties of the limestone feed and the ash content of the coal can significantly affect PM emissions.

Some sort of particulate control is generally applied to most furnaces. Rudimentary fallout chambers and cyclone separators are commonly used to control the larger particles. Fabric and gravel bed filters, wet (commonly venturi) scrubbers, and electrostatic precipitators are used for secondary control.

Carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxides (NO) are all produced in furnaces. Sulphur dioxide emissions are influenced by several factors, including the sulphur content of the fuel, the sulphur content and mineralogical form (pyrite or gypsum) of the stone feed, the quality of lime being produced, and the type of furnace. Due to variations in these factors, plant-specific SO emission factors are likely to vary significantly from the average emission factors presented here. The dominant source of sulphur emissions is the furnace's fuel, and the vast majority of the fuel sulphur is not emitted because of reactions with calcium oxides in the furnace. Sulphur dioxide emissions may be further reduced if the pollution equipment uses a wet process or if it brings CaO and SO into intimate contact.

Hazard Summary of Lime

- Calcium Oxide can affect one when one breathes it in.
- Contact can severely irritate and burn the eyes and skin.
- Breathing Calcium Oxide can irritate the lungs causing coughing and/or shortness of breath. Higher exposures may cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath.
- Long-term exposure can irritate the nose causing a hole in the "bone" dividing the inner nose, and can cause brittle nails and thickening and cracking of the skin.
- Calcium Oxide is a dot corrosive chemical

10.2 Suggestions on treatment of such pollutants

The measures outlined below are some of the suggestions that can be used to minimize environmental pollution occurring from the lime production plant.

- The efficiency of the furnace should be properly justified, so that there is minimum loss of lime in the atmosphere.
- The carbon dioxide can be absorbed using monoethanolamine (MEA).
- Sulphur dioxide can also be removed by absorbing it with a solvent like water.
- Nitrogen dioxide can also be treated via catalyzed conversion by reacting it with hydrogen to yield nitrogen and water which are harmless.
- Carbon monoxide (a very poisonous gas) is also treated by reacting it with hydrogen in a process known as catalyzed conversion of impurities.

CHAPTER ELEVEN

11.0 START UP AND SHUT DOWN PROCEDURE

Start up time may be defined as the time span between end of construction and the beginning of normal operations. Start up and shut down procedure must proceed safely and be flexible enough to be carried out in various ways. In other words, the start up and shut down of the lime plant should be such that it can be easily and safely operated. The operating limits of the lime plant should not be exceeded and dangerous mixtures must not be formed as a result of abnormal states of concentration, composition, temperature, phase, pressure, reactants and products.

It should be noted that some items of actions must be completed before even the start up of the lime plant in order to prepare the lime plant for the start up operation. The items of actions are:

i. All scaffolds and temporary piping and supports should be removed.

ii. Lines and equipment should be flushed out.

iii. Pumps, motors/turbines and compressors should be run.

iv. Hydrostatic or pneumatic lines and equipment should be tested.

v. Laboratory and sampling schedule should be prepared.

vi. All instruments should be inspected and tested.

11.1 Start Up Procedures

For the lime plant designed, the following are the start up procedures:

i. The source should be open to be supplied to the furnace for calcinations.

ii. The furnace should be started up using auxiliary fuel.

iii. The furnace should be heated up and maintained at the operating temperature.

iv. The inlet and outlet valves of the furnace should be opened up.

v. All the inlet and outlet valves to the furnace should be shut as soon as the feed enters the reactor in order to achieve maximum conversion.

vi. The outlet value of the reactor should be opened for the evacuation of the reactor contents.

vii. The outlet valve of the furnace should be locked before opening the inlet valve before further entering of the feed into the reactor.

11.2 Shut Down Procedures

The shut down procedures for the lime plant are as outlined below

i. The supply of limestone to the furnace should be stopped

ii. The supply of fuel to the furnace should be cut off.

iii. All the purge valves should be opened to discharge unconverted reactants.

CHAPTER TWELVE

12.0 SITE FOR LIME PLANT LOCATION

The location of the lime plant can have a crucial effect on the profitability of the lime production project and the scope for future expansion. Many factors must be considered when selecting a suitable site, and a review of the principal factors will be given in this chapter of this design project for the production of lime. The principal factors to be considered are:

i. Location, with respect to the marketing area.

ii. Raw materials supply.

iii. Transport facilities.

iv. Availability of labour.

v. Availability of utilities.

vi. Availability of suitable land.

vii. Environmental impact and effluent disposal.

viii. Local community considerations.

ix. Climate.

x. Political and strategic considerations. (Sinnot, 1999)

12.1 Factors Considered for Site and Lime plant Location

The factors considered for site and lime plant location are as described thus.

12.1.1 Location, with respect to the marketing area

For a material produced in bulk quantities such as the lime where the cost of the product per tonne is relatively low and the cost of transport is a significant fraction of the sales price, the lime plant should be located close to the primary market. This consideration will be less important for low volume production, high-priced products; such as pharmaceuticals. (Sinnot, 1999)

12.1.2 Raw materials

The availability and price of suitable raw materials will often determine the site location. Lime plants producing bulk chemical as the lime plant are best located close to the source of the major raw materials (which is limestone); where this is also close to the marketing area. (Sinnot, 1999)

12.1.3 Transport

The transport of materials and products to and from the lime plant will be an overriding consideration for site selection.

If practicable, a site should be selected that is close to at least tow major forms of transport: road, rail, waterway (canal or river), or a sea port. Road transport is being increasingly used, and is suitable for local distribution from a central warehouse. Rail transport will be cheaper for the long-distance transport of bulk chemicals.

Air transport is convenient and efficient for the movement of personnel and essential equipment and supplies, and the proximity of the site to a major airport should be considered. (Sinnot, 1999)

12.1.4 Availability of labour

Labour will be needed for construction of the lime plant and its operation. Skilled construction workers will usually be brought in from outside the site area, but there should be an adequate pool of unskilled labour available locally; and labour suitable for training to operate the lime plant. Skilled tradesmen will be needed for lime plant maintenance. Local trade union customs and restrictive practices will have to be considered when assessing the availability and suitability of the local labour for recruitment and training. (Sinnot, 1999)

12.1.5 Utilities

Chemical processes invariably require large quantities of water for cooling and general process use, and the lime plant must be located near a source of water of suitable quality. Process water may be drawn from a river, from wells, or purchased from a local authority.

At some sites, the cooling water required can be taken from a river or lake, or from the sea; at other locations cooling towers will be needed. Electrical power will be needed at all sites.

Electrochemical processes that require large quantities of power need to be located close to a cheap source of power. A competitively priced fuel must be available on site for steam and power generation. (Sinnot, 1999)

12.1 Selection of Site

The suburb of Sokoto, Sokoto State, Nigeria, has been chosen for as the site for lime plant. The selection has been based on some requirements, which the site was able to meet among the factors for the site selection discussed above. The justifications for the selected site are as follows:

12.2 Justification of the Selected Site

The suburb of Sokoto, Sokoto State, Nigeria, has been chosen as the site for this lime plant due to the fact that the site was justified to worth it. The justifications are as follows:

12.3.1 Availability of raw materials

The major raw material in the production of lime is the limestone because hot air for the furnace is available everywhere. Looking at it very well, the major source of this major raw material, limestone is the Sokoto area of the country. So, siting the lime plant in the suburb of Sokoto in Sokoto State is siting the plant close the source of the raw material.

12.3.2 Nearness to marketing area

Since lime is used in the production of other products, siting its plant close to the place of primary marketing area, that is, Sokoto Portland Cement Company, will be very ideal.

12.3.3 Transport

The good and many means of transportation present in the area will ensure effective transportation of the raw materials, products and even the skilled experts at low cost. Another advantage is that Sokoto has good road network.

12.3.4 Availability of labour

For the fact that Sokoto is located in limestone region, youths, both skilled and unskilled, are now trooping into the area to seek their source of living via the cement company present in the area. That is to say, all kinds of labour force are available there.

12.3.5 Climate

The absence of adverse climatic conditions such as too low temperature or too high wind loads or earthquakes has made Sokoto a good site for the lime plant.

12.3.6 Political and strategic considerations

In an attempt to woo investors to Sokoto State, the Sokoto State government has given capital grants and other inducements to direct new investment to Sokoto State. Thus, availability of such grants is an overriding consideration in selecting Sokoto as the favourable site for the lime plant.

12.3.7 Utilities

Since the process of lime production requires large quantities of services such as hot air for the dryers and furnace, cooling water for the coolers and other services, it is important that the lime plant should be sited in a place where there is abundance of water; Sokoto is one of such areas.

12.4 Lime plant Layout

The economic construction and operation of a process unit will depend on how well the lime plant equipment specified on the process flow sheet and laid out. The principal factors to be considered are:

a. Economic consideration: construction and operation cost.

b. The process requirement

c. Convenience of operation

d. Convenience of maintenance

e. Safety

f. Future expansion

g. Modular construction

12.4.1 Costs

The cost of construction can be minimized by adopting a layout that gives shortest run of connecting pipes between equipment, and adopting the least amount of structural steel work. However, this will not necessarily be the best arrangement for operation and maintenance.

12.4.2 Process requirement

All the required equipments have to be placed properly within process. Even the installation of the auxiliaries should be done in such a way that it will occupy the least space.

12.4.3 Operation

Equipment that needs to have frequent operation should be located convenient to the control room. Valves, sample points, and instruments should be located at convenient position and height. Sufficient working space and headroom must be provided to allow easy access to equipment.

12.4.4 Maintenance

Heat exchangers need to be sited so that the tube bundles can be easily withdrawn for cleaning and tube replacement. Vessels that require frequent replacement of catalyst or packing should be located on the outside of buildings. Equipment that requires dismantling for maintenance, such as compressors and large pumps, should be placed under cover.

12.4.5 *Safety*

Blast walls may be needed to isolate potentially hazardous equipment, and confine the effects of an explosion. At least two escape routes for operator must be provided from each level in the process building.

12.4.6 *Lime plant expansion*

Equipment should be located so that it can be conveniently tied in with any future expansion of the process. Space should be left on pipe alleys for future needs, service pipes over-sized to allow for future requirements.

12.4.7 *Modular construction*

In recent years, there has been a move to assemble sections of the lime plant at the manufacturer site. These modules will include the equipment, structural steel, piping and instrumentation. The modules then transported to the lime plant site, by road or sea.

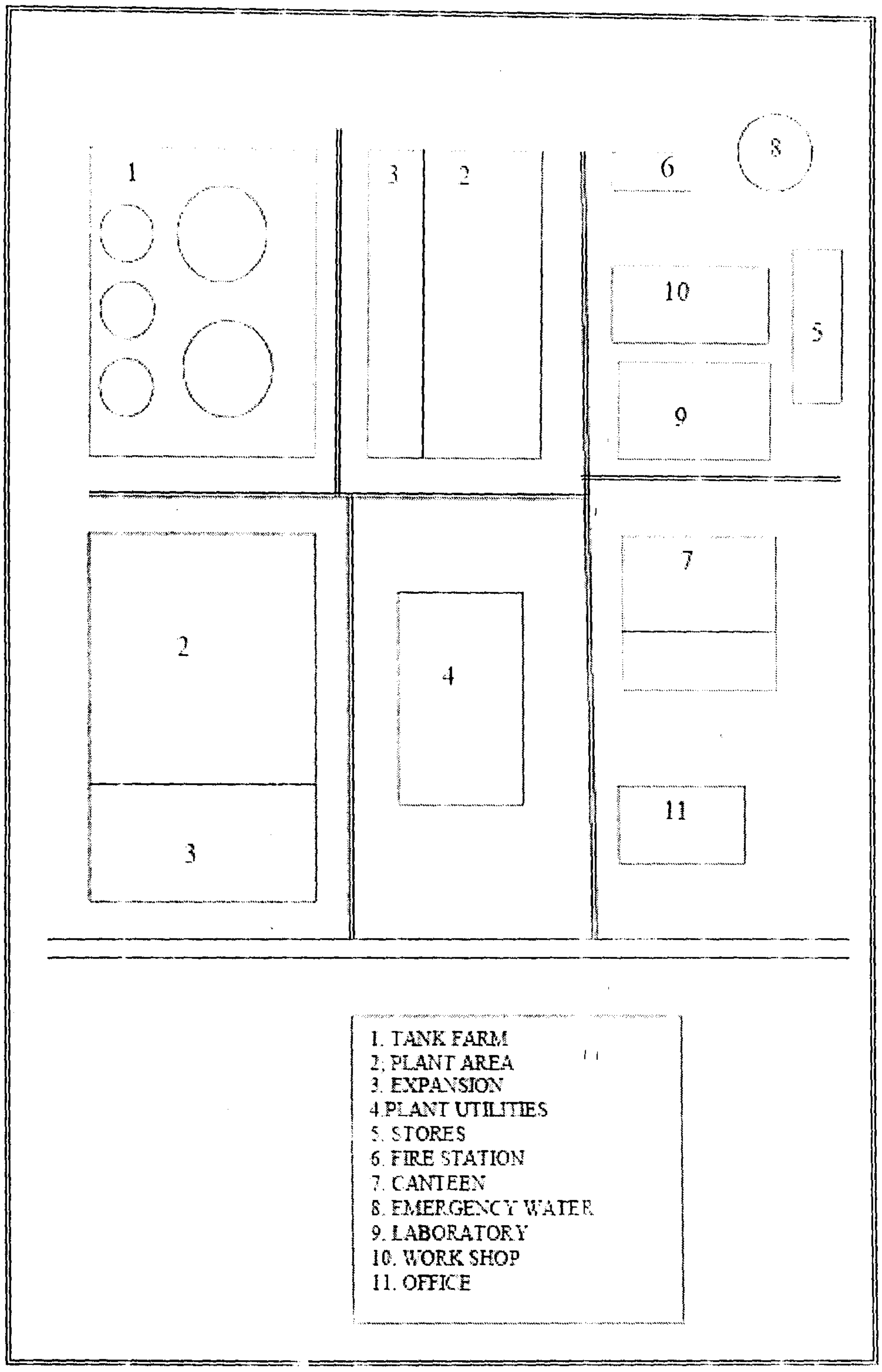


Fig. 12.1: Layout of lime plant

CHAPTER THIRTEEN

13.0 ECONOMIC ANALYSIS

Chemical plants are built to make a profit, and an estimate of the investment required and the cost of production are needed before the profitability of a project can be assessed.

For any industrial plant to be put into operation, huge sum of money must have been invested in it to purchase and install the necessary machinery and equipment. Land and service facilities must be obtained and the plant must be erected complete with the piping, controls, and service. In addition to all these cost, it is necessary to have money available for the payment of expenses involved in plant operation.

The capital requires to have the necessary manufacturing and plant facilities is called the fixed capital investment. That which is necessary for operation of the plant is termed the working capital. The sum of the fixed investment and the working capital is the total capital investment.

13.1 METHOD OF COSTING

The method of costing used in this project is ***Marshall and Smith Method.***

13.2 EQUIPMENT COST ANALYSIS

The cost analysis of equipments in the plant is carried out using the cost equation of each process

equipment as proposed by Marshall and Smith.

13.2.1 COST OF BIN

The cost of bin is given as

$$PC_{bin} = \frac{M\_S}{280} \cdot \left(101.9 \cdot D^{1.066} H^{0.802} \cdot F_c\right)$$

where D = diameter

H = height

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $M\_S := 1100$

For the bin

$D_{bin} = 1.65\ m$

$H_{bin} = 4.06\ m$

Choosing carbon steel for the bin,

$F_m := 1$

$F_p := 1$

$F_c := F_m \cdot F_p$

$F_c = 1.00$

So, from

$$PC_{bin} := \frac{M\_S}{280} \cdot \left[101.9 \cdot \left(\frac{D_{bin}}{m}\right)^{1.066} \left(\frac{H_{bin}}{m}\right)^{0.802} \cdot F_c \right]$$

$PC_{bin} = 308929.92$ Naira

13.2.2 COST OF DRYER

The cost of dryer is given as

$$PC_{dryer} = \frac{M\_S}{280} \cdot \left(101.3 \cdot A^{0.65} \cdot F_c\right)$$

where D = diameter

H = height

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $M\_S := 1100$

For the dryer

$A_{dryer} = 53.31\ m^2$

$D_{dryer} = 8.24\ m$

Choosing carbon steel for the dryer,

$F_m := 1$

$F_p := 1$

$F_c := F_m \cdot F_p$ $\qquad F_c = 1.00$

So, from

$$PC_{dryer} := \frac{M\_S}{280} \cdot \left[101.3 \cdot \left(\frac{A_{dryer}}{m^2} \right)^{0.65} \cdot F_c \right]$$

$PC_{dryer} = 775503.89$ Naira

13.2.3 COST OF CRUSHER

The cost of crusher is given as

$$PC_{crusher} = \frac{M\_S}{280} \cdot \left(101.9 \cdot D^{1.066} H^{0.802} \cdot F_c \right)$$

where D = diameter

H = height

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $\qquad M\_S := 1100$

For the crusher,

$D_{crusher} := d_{crusher}$ $\qquad d_{crusher} = 1.67\,m$

$H_{crusher} := h_{crusher}$ $\qquad h_{crusher} = 3.12\,m$

Choosing carbon ste[illegible] bin,

$F_m := 1$

$F_p := 1$

$F_c := F_m \cdot F_p$ $\qquad F_c = 1.00$

So, from

$$PC_{crusher} := \frac{M\_S}{280} \cdot \left[101.9 \cdot \left(\frac{D_{crusher}}{m} \right)^{1.066} \left(\frac{H_{crusher}}{m} \right)^{0.802} \cdot F_c \right]$$

$PC_{crusher} = 253599.84$ Naira

13.2.4 COST OF SCREENER

The cost of screener is given as

$$PC_{screener} = \frac{M\_S}{280} \cdot \left(101.3 \cdot A^{0.65} \cdot F_c\right)$$

where $D = \text{diameter}$

$H = \text{height}$

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $M\_S := 1100$

For the bin

$A_{screener} = 20.37\,m^2$

$F_m := 1$

$F_p := 1$

$F_c := F_m \cdot F_p$ $F_c = 1.00$

So, from

$$PC_{screener} := \frac{M\_S}{280} \cdot \left[101.3 \cdot \left(\frac{A_{screener}}{m^2}\right)^{0.65} \cdot F_c\right]$$

$PC_{screener} = 414906.63$ Naira

13.2.5 COST OF FURNACE

The cost of furnace is given as

$$PC_{furnace} = \frac{M\_S}{280} \cdot \left(5520 \cdot Q^{0.65} \cdot F_c\right)$$

where Q = "heat duty"

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $M\_S := 1100$

For the furnace $Q_{furna} := 3.812 \times 10^5 \cdot \frac{kJ}{hr}$ $D_{furnace} = 1.60\,m$

Choosing carbon steel for the furnace,

$$F_m := 1$$

$$F_p := 1$$

$$F_c := F_m \cdot F_p \qquad F_c = 1.00$$

So, from

$$PC_{furnace} := \frac{M\_S}{280} \cdot \left[101.3 \cdot \left(\frac{Q_{furnace}}{\frac{kJ}{hr}} \right)^{0.65} \cdot F_c \right] \qquad PC_{furnace} = 248262322.38\ \text{Naira}$$

13.2.6 COST OF COOLER

The cost of cooler is given as

$$PC_{cooler} = \frac{M\_S}{280} \cdot \left(101.3 \cdot A^{0.65} \cdot F_c \right)$$

where D = diameter

H = height

$F_c = F_m \cdot F_p$

and M_S = "Marshall and Smith index and has a numerial value of" $M\_S := 1100$

For the cooler

$$A_{cooler} = 71.03\,m^2$$

Choosing carbon steel for the cooler,

$$F_m := 1$$

$$F_p := 1$$

$$F_c := F_m \cdot F_p \qquad F_c = 1.00$$

So, from

$$PC_{cooler} := \frac{M\_S}{280} \cdot \left[101.3 \cdot \left(\frac{A_{cooler}}{m^2} \right)^{0.65} \cdot F_c \right] \qquad PC_{cooler} = 934499.54\ \text{Naira}$$

13.3 Total Purchase Cost of Equipments

The total purchased cost of equipments is, calculated as the sum of individual cost of purhase of

equipments as,

$$PC_T := PC_{bin} + PC_{dryer} + PC_{crusher} + PC_{screener} + PC_{furnace} + PC_{cooler}$$

$$PC_T = 250949762.20 \text{ Naira}$$

Assuming that the initial fixed capital investment for the plant is the total purchased cost of equipments, the initial fixed capital investment is then equal to

$$FCI := PC_T$$

$$FCI = 250949762.20 \text{ Naira}$$

13.4 Estimation of Total Capital Investment

I. Direct Costs

A. Equipment + installation + instrumentation + piping + electrical + insulation + painting

1. ***Purchased equipment cost (PEC),*** 15-40% of fixed capital investment

Assuming $PEC := 37\% \cdot FCI$ $\quad PEC = 92851412.01 \text{ Naira}$

2. ***Installation, including insulation and painting,*** 25-55% of purchased equipment cost

Assume $Insta := 50\% \cdot PEC$ $\quad Insta = 46425706.01 \text{ Naira}$

3. ***Instrumentation and controls, installed,*** 6-30% of purchased equipment cost

Assuming

$Instr := 25\% \cdot PEC$ $\quad Instr = 23212853.00 \text{ Naira}$

4. ***Piping installed,*** 10-80% of purchased equipment cost

Assuming

$Pip := 70\% \cdot PEC$ $\quad Pip = 64995988.41 \text{ Naira}$

5. ***Electrical, installed,*** 10-40% of purchased equipment cost

Assuming

$Elect := 35\% \cdot PEC$ $\quad Elect = 32497994.20 \text{ Naira}$

So, the cost of equipment, installation, instrumentation, piping, electrical, insulation and

painting is given as

$$CA := PEC + Insta + Instr + Pip + Elect$$

$$CA = 259983953.64 \text{ Naira}$$

B. Buildings, process and auxiliary, 10-70% of purchased equipment cost

Assuming

$$Build := 65\% \cdot PEC$$

$$Build = 60353417.81 \text{ Naira}$$

C. Service facilities and yard improvements, 40-100% of purchased

equipment cost

Assuming

$$Servi := 70\% \cdot PEC$$

$$Servi = 64995988.41 \text{ Naira}$$

D. Land, 1-2% of fixed capital investment or 4-8% of purchased equipment cost)

Assuming

$$Lan := 5\% \cdot PEC$$

$$Lan = 4642570.60 \text{ Naira}$$

Thus, the direct cost is equal to

$$Direct\_Cost := CA + Build + Servi + Lan$$

$$Direct\_Cost = 389975930.46 \text{ Naira}$$

II. Indirect costs: expenses which are not directly involved with material and labour of actual installation of complete facility (15-30% of fixed capital investment)

A. Engineering and supervision, 5-30% of direct cost

Assuming

$$Engin := 27\% \cdot Direct\_Cost$$

$$Engin = 105293501.22 \text{ Naira}$$

B. Construction expense and contractor's fee, 6-30% of direct cost

Assuming

$$Const := 55\% \cdot Direct\_Cost$$

$$Const = 214486761.75 \text{ Naira}$$

C. Contingency, 5-15% of direct cost

Assuming

$$Conti := 13\% \cdot Direct\_Cost$$

$$Conti = 50696870.96 \text{ Naira}$$

Thus, indirect cost is equal to

Indirect_Cost := Engin + Const + Conti

Indirect_Cost = 370177133.93 Naira

III. *Fixed Capital Investment:*

Fixed capital investment to be Direct cost + Indirect cost

Fixed_CI := Direct_Cost + Indirect_Cost

Fixed_CI = 760453064.39 Naira

IV. *Working Capital,* 11-20% of fixed capital investment

Assuming Working_C := 11% · Fixed_CI

Working_C = 83649837.08 Naira

V. *Total Capital Investment (TCI):*

Total capital investment to be Fixed capital investment + Working capital

Assuming Total_CI := Fixed_CI + Working_C

Total_CI = 844102901.47 Naira

Estimation of Total Product Cost:

I. ***Manufacturing Cost*** to be Direct production + Fixed charges + Plant overhead cost

A. ***Fixed Charges,*** 10-20% of total product cost)

i. ***Depreciation,*** This depends on life period, salvage value and method of calculation

- about 13% of FCI for machinery and equiupment and 2-3% of building value for buildings

Assuming

Depre := 13% · Fixed_CI + 3% · Build

Depre = 100669500.90 Naira

ii. ***Local Taxes,*** 1-4% of fixed capital investment

Assuming

Tax := 3% · Fixed_CI

Tax = 22813591.93 Naira

iii. ***Insurance,*** 0.4-1% of fixed capital investment)

Assuming

Insur := 0.75% · Fixed_CI

Insur = 5703397.98 Naira

iv. ***Rent,*** 8-12% of value of fixed capital investment

Assuming

Ren := 12% · Fixed_CI

Ren = 91254367.73 Naira

Thus, fixed charges is given as

$\text{Fixed} := \text{Depre} + \text{Tax} + \text{Insur} + \text{Ren}$

$\text{Fixed} = 220440858.55$ Naira

Assuming

$\text{Fixed\_C} = 15\% \cdot \text{TPC}$

making total product cost, TPC, the subject of the formula,

$$\text{TPC} = \frac{\text{FC}}{15\%}$$

$$\text{TPC} := \frac{\text{Fixed}}{15\%}$$

$\text{TPC} = 1469605723.64$ Naira

B. *Direct Production Cost:*

i. ***Raw materials,*** 10-50% of total product cost)

Assuming

$\text{Raw\_mat} := 49\% \cdot \text{TPC}$

$\text{Raw\_mat} = 720106804.58$ Naira

ii. ***Operating Labour (OL),*** 10-20% of total product cost

Assuming

$\text{OperL} := 16\% \cdot \text{TPC}$ $\text{OperL} = 235136915.78$ Naira

iii. ***Direct Supervisory and Clerical Labour (DS & CL),*** 10-25% of OL

Assuming

$\text{DireS} := 20\% \cdot \text{OperL}$

$\text{DireS} = 47027383.16$ Naira

iv. ***Utilities,*** 10-20% of total product cost

Assuming

$\text{Util} := 18\% \cdot \text{TPC}$

$\text{Util} = 264529030.26$ Naira

v. ***Maintenance and repairs (M & R),*** 2-10% of fixed capital investment

Assuming

$\text{Maint} := 5\% \cdot \text{Fixed\_CI}$

$\text{Maint} = 38022653.22$ Naira

vi. ***Operating Supplies,*** 10-20% of M & R or 0.5-1% of FCI

Assuming

$\text{OperS} := 15\% \cdot \text{Maint}$

$\text{OperS} = 5703397.98$ Naira

vii. ***Laboratory Charges,*** 10-20% of OL

Assuming

$\text{Lab} := 18\% \cdot \text{OperL}$ $\text{Lab} = 42324641.84$ Naira

viii. Patent and Royalties, 0-6% of total product cost

Assuming

$\mathrm{Paten} := 6\% \cdot \mathrm{TPC}$ $\qquad \mathrm{Paten} = 88176343.42$ Naira

Thus, direct production cost is

$\mathrm{DPC} := \mathrm{Raw\_mat} + \mathrm{OperL} + \mathrm{DireS} + \mathrm{Util} + \mathrm{Maint} + \mathrm{OperS} + \mathrm{Lab} + \mathrm{Paten}$

$\mathrm{DPC} = 1441027173.24$ Naira

C. Plant Overhead Costs, 50-70% of operating labour, supervision, and maintenance or 5-15% of total product cost); includes for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, salvage, laboratories, and storage facilities.

Considering the plant overhead cost to be 55% of OL, DS & CL and M & R

Therefore,

$\mathrm{Plant} := 55\% \cdot (\mathrm{OperL} + \mathrm{DireS} + \mathrm{Maint})$ $\qquad \mathrm{Plant} = 176102823.69$ Naira

Manufacture cost = Direct production cost + Fixed charges + Plant overhead cost

$\mathrm{Manuf} := \mathrm{DPC} + \mathrm{Fixed} + \mathrm{Plant}$ $\qquad \mathrm{Manuf} = 1837570855.47$ Naira

II. General Expenses = Administrative costs + distribution and selling costs + research

and development costs

A. Administrative costs, 2-6% of total product cost

Assuming

$\mathrm{Admin} := 4.5\% \cdot \mathrm{TPC}$ $\qquad \mathrm{Admin} = 66132257.56$ Naira

B. Distribution and Selling Costs, 2-20% of total product cost; includes costs for sales offices, salesmen, shipping, and advertising.

Assuming

$\mathrm{Distr} := 17\% \cdot \mathrm{TPC}$ $\qquad \mathrm{Distr} = 249832973.02$ Naira

C. Research and Development Costs, about 3% of total product cost

Assuming

$\mathrm{Resea} := 3\% \cdot \mathrm{TPC}$ $\qquad \mathrm{Resea} = 44088171.71$ Naira

Thus, general expenses,

$$\text{Gener} := \text{Admin} + \text{Distr} + \text{Resea}$$

$$\text{Gener} = 360053402.29\ \text{Naira}$$

IV. Total Production Cost = Manufacture Cost + General Expenses

$$\text{TProdC} := \text{Manuf} + \text{Gener}$$

$$\text{TProdC} = 2197624257.76\ \text{Naira}$$

V. Gross Earnings/Income:

The selling price of lime is equal to

$$\text{Selling\_price} := 32.5 \cdot \frac{\text{Naira}}{\text{kg}}$$

$$\text{Quantity\_produced} := 10160.47 \cdot \frac{\text{kg}}{\text{hr}} \qquad \text{Quantity\_produced} = 89064777.75 \frac{\text{kg}}{\text{yr}}$$

Assuming that the attainment is $\text{Attainment} := 331 \cdot \text{day}$

Total income = Selling price x quantity of product manufactured

$$\text{Total\_income} := \text{Selling\_price} \cdot \text{Quantity\_produced} \cdot \text{Attainment}$$

$$\text{Total\_income} = 2623230144.60\ \text{Naira}$$

Gross income = Total income - Total Product Cost

That is, $\text{Gross\_income} := \text{Total\_income} - \text{TProdC}$

$$\text{Gross\_income} = 425605886.84\ \text{Naira}$$

Assuming the tax rate to be $\text{Tax\_rate} := 15\%$

Net profit = Gross income - Taxes

$$\text{Taxes} := \text{Tax\_rate} \cdot \text{Gross\_income} \qquad \text{Taxes} = 63840883.03\ \text{Naira}$$

$$\text{Net\_profit} := \text{Gross\_income} - \text{Taxes}$$

$$\text{Net\_profit} = 361765003.81\ \text{Naira}$$

Rate of Return:

$$\text{Rate\_of\_return} = \frac{\text{Net\_profit}}{\text{Total\_CI}} \cdot 100\%$$

Therefore,

$$\text{ROR} := \frac{\text{Net\_profit}}{\text{Total\_CI}} \cdot 100\% \qquad \text{ROR} = 42.86\%$$

Pay-Back Period:

The pay-back period is calculated as the reciprocal of the rate of return.

Therefore,

$$PBP := \frac{1}{ROR} \cdot yr \qquad PBP = 2.33\,yr$$

which is approximately equal to $PBP = 2\,yr$

Cash Flow

Cash flow is the difference between the amount earned and the amount expended.

$$Cash\_Flow := Total\_income - TProdC \qquad Cash\_Flow = 425605886.84\,Naira$$

Net Present Worth of the Project

The net present worth (NPW) of cash flow in year n is given as

$$NPW = \sum_{i=1}^{n} \frac{Cash\_Flow}{(1+r)^n}$$

$r := ROR \qquad n := 1$

Therefore,

$$NPW := \sum_{i=1}^{n} \frac{Cash\_Flow}{(1+r)^n} \qquad NPW = 297922485.86\,Naira$$

Discounted Cash Flow Rate or Return

The discounted cash flow is the interest rate that will make the condition given as

$$DCF = \sum_{i=1}^{n} \frac{Cash\_Flow}{(1+r)^n} = 0$$

Using trial-and-error calculations as suggested by Sinnot R. K.

$r := 45 \cdot \% \qquad n := 65 \qquad DCFRR := r$

$$DCF := \sum_{i=1}^{n} \frac{Cash\_Flow}{(1+r)^n} \qquad DCF = 0$$

Therefore, the Discounted Cash Flow Rate of Return (DCFRR) is equal to $DCFRR = 45.00\%$.

Return on Investment

This is calculated as given thus.

Return on investment (ROI) is given by the expression,

$$ROI = \frac{Total\_profit\_less\_depreciation}{Total\_investment}$$

That is,

$$ROI := \frac{Total\_income - Depre}{Total\_income} \cdot 100\% \qquad ROI = 96.16\%$$

Project Income and Expenses Statement for 2005-2008

This plant was designed to produce 10 tonnes per hr ($Basis := 10 \cdot \frac{tonne}{hr}$) of lime. Making the plant attainment to be $Attainment = 331.00\,day$, the plant is thus required to produce

$Basis \cdot Attainment = 79440.00\,tonne$

It is expected that the performance of the plant should increase every year. For instance, assuming that the plant operates at 70% capacity in the first year, 80% capacity in the second year, 90% capacity in the third year and, finally, 100% capacity in the fourth year. The project income and expenses statement for these four years are as shown below.

Table 13.1: Projected income and expenses statement for the year 2005 to 2008

	YEARS			
DESCRIPTION	***2005***	***2006***	***2007***	***2008***
Tonnes/hr	10.00	11.43	12.86	14.29
Capacity (%)	70	80	90	100
REVENUE	*Amount in Naira*			
Net sales	2.62E+09	2997977257	3372724414	3747471571
EXPENDITURE				
Raw material	720106800	822979200	925851600	1028724000
Factory labour	235136920	268727908.6	302318897.1	335909885.7
Depreciation	100669500	115050857.1	129432214.3	143813571.4
Overhead	176102820	201260365.7	226417911.4	251575457.1
TOTAL	1232016040	1408018331	1584020623	1760022914
PROFIT				
Before tax	425605890	486406731.4	547207572.9	608008414.3
Tax	63840883	72961009.14	82081135.29	91201261.43
Net profit	361765007	413445722.3	465126437.6	516807152.9

Conclusion on the Economic Viability of the Project

The total production cost of the plant which is $TProdC = 2197624257.76\,Naira$ and a net profit of $Net\_profit = 361765003.81\,Naira$ have revealed that the project is economically viable with a pay back period of approximately $PBP = 2.33\,yr$.

CHAPTER FOURTEEN

14.0 RECOMMENDATIONS TO THE INDUSTRIALIST

Having carried out the design of lime plant, the following recommendations are made to the industrialists to be noted during the construction, start-up and operating phases of the work:

i. Adequate data and technological parameters should be at the possession of the lime plant operations at all time to forestall any unwanted accident.

ii. Routine turn around lime plant maintenance should be of paramount importance in the design. An articulate and organised maintenance team should safeguard quick lime plant shut down and ensure equipment salvage value. This will also take care of schedule, slippage, cost over-run and possible re-work.

iii. Personnel should undergo routine training about new work ethic and equipments to improve their knowledge of the lime plant operation and increase overall lime plant productivity.

iv. Procurement of raw materials and equipments should be based on strict regulation of specification and maximum quality.

v. Lime plant should not be operated above the design specification to avoid abnormal conditions and explosions.

vi. The implementation of this design work must be adequately supervised by the experts.

vii. The lime plant should be sited close to the source of raw materials.

viii. Alternative sources of energy should be available at all times to avoid lime plant failure and possible sources of failure.

ix. The water and air around the lime plant should be monitored regularly to ensure compliance with the Environmental Protection Agency Standards.

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