

**DESIGN OF A FLUIDIZED BED DECARBONISATION  
FURNACE TO PRODUCE 10 TONNES/HOUR OF QUICKLIME  
FROM LIMESTONE.**

**BY**

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**2000/9657EH**

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

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

**OCTOBER 2006**

## DECLARATION

I hereby declare that this Design of a Fluidized Bed Decarbonisation Furnace to Produce 10 Tonnes/Hour of Quicklime From Limestone. was wholly under taken by me under the guidance and supervision of Professor O. Odigure. It has never been submitted to chemical Engineering for award of degree.

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Abdullahi Yusuf Paiko

## CERTIFICATION

This is certify that this Design of a Fluidized Bed Decarbonisation Furnace to Produce 10 Tonnes/Hour of Quicklime From Limestone” was done by Abdullahi Yusuf Paiko under the supervision of Professor J.O. Odigure and submitted to the chemical Engineering Department, Federal University of Technology Minna, In partial fulfillment of the requirement for the award of Bachelor of Engr. (b.Eng.(B. Eng.) Degree in Chemical Engineering.

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Professor, J.O Odigure

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Date & Signature

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Dr. M. Edoga

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Date & Signature

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External Examiner

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Date & signature

## DEDICATION

This project report is dedicated to the Glorious one: ALLAH, who saw me through the darkest hours when I was in search of relevant materials to carry out this project and also for keeping me alive to be part of this programme today.

A special dedication also goes to my father Alhaji Yusuf Paiko for his financials and moral assistance through my B. Eng. Academic pursuit

Also this work is dedicated to all members of my family and my friends which include, Umar Ndanusa, Adamu Usman, Akeem Olatunji, and Suleiman Abubakar Idris.

Lastly, real dedication is for you my best and closest friend Miss Amina, you are such a qualify person that every body desires (I Love you.)

## ACKNOWLEDGEMENT

I wish to express my sincere thanks and gratitude to my supervisor, Professor J.O Odigure for going through the manuscript for useful corrections and my coordinator Engr. Kovo. I sincerely appreciate your effort towards making this design a success God bless you all.

## ABSTRACT

The aim of this project is the design of a fluidized bed decarbonisation furnace to produce 10 tonnes/hour of quicklime from limestone. The process used in this project made use of fluidized bed reactor to carry out the calcination (or decarbonisation) instead of kiln. In the design of this plant to produce 10 tonnes/hour of quicklime, 19718.28kg/hr of limestone was passed into the furnace. The various units involved in the plant such as the bin, pre-crusher, screener 1, crusher, screener 2, dryer, fluidized bed furnace, cyclone and the cooler were designed. Finally, the economic analysis of the plant showed the Net profit and the total capital investment of the plant were ₦1, 803,000,000 and ₦5, 970, 000,000 respectively. The plant was found to be economically viable with the rate of return of 30.155% and a pay back period of approximately 3 years.

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## CHAPTER ONE

### 1.0 INTRODUCTION

#### 1.1 Quicklime

Quicklime is used in a wide range of products, for example as a fluxing agent in steel refining, as a binder in building and construction, and in water treatment to precipitate impurities. Quicklime is also used extensively for the neutralization of acidic components of industrial effluent and flue gases. The lime making process consists of the burning of calcium and/or magnesium carbonates to liberate carbon dioxide and to obtain the derived oxide ( $\text{CaCO}_3 = \text{CaO} + \text{CO}_2$ ).

The calcium oxide product from the kiln is generally crushed, milled and/or screened before being conveyed to silo storage. From the silo, the burned lime is either delivered to the end user for use in the form of quicklime, or transferred to a hydrating plant where it is reacted with water to produce slaked lime.

The term lime includes quicklime and slaked lime and is synonymous with the term lime products. Quicklime, or burnt lime, is calcium oxide (CaO). Slaked lime consist mainly of calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) and includes hydrated lime (dry calcium hydroxide powder), milk of lime and lime putty (dispersions of calcium hydroxide particles in water).

Quicklime production generally uses between 1.4 and 2.2 tonnes of limestone per tonne of saleable quicklime. Consumption depends on the type of product, the purity of the limestone, the degree of calcination and the quantity of waste products. Most of the balance is lost from the process as carbon dioxide emission to air. The lime industry is a highly energy-intensive industry with energy accounting for up to 50% of total production costs. Kilns are fired with solid, liquid or gaseous fuels. The use of natural gas has increased substantially over the last few years. In 1995 the most commonly used fuels were natural gas (48%) and

coal, including hard coal, coke, lignite and petcoke, (36%) followed by oil (15%) and other fuels (1%).

### 1.1.1 Properties of Quicklime

Table 1.1: Properties of lime

<b>General</b>	
Name	Calcium oxide
Chemical formula	CaO
Appearance	White solid
<b>Physical</b>	
Formula weight	56.1 amu
Melting point	2572 K (2927 °C)
Boiling point	2850 K (3500 °C)
Density	$3.3 \times 10^3 \text{ kg/m}^3$
Crystal structure	Face-Centered Cubic
Solubility	Hydrolysed

(<http://www.answers.com/topic/calcium-oxide>)

### 1.1.2 Importance of Lime

Lime itself may be used for medicinal purposes, insecticides, plant and animal food, gas absorption, precipitation, dehydration, and causticizing. It is employed as a reagent in the sulfite process for paper, making, dehairing hides, the manufacture of high grade steel and cement, water softening, recovery of by product ammonia, and the manufacture of soap, rubber, varnish, refractories, and sand-lime brick. Lime is indispensable for use with mortar and plaster and serves as a basic raw material in the production of calcium salts and for improving the

quality of certain soils. Either directly or indirectly, limestone and lime are employed in more industries than any other natural substance. (Shreeve's, 1983)

## **1.2 Limestone**

### **1.2.1 Sources of Limestone**

The term limestone is used to describe sedimentary rocks containing calcium carbonate, which is present as the minerals calcite and aragonite. Limestone may contain varying amounts of dolomite (calcium-magnesium carbonate) as well as silica and alumina.

Limestone is mainly used for manufacturing Portland cement and quicklime, as a flux in steel making, in copper and lead smelting, in glass manufacturing, alumina refining and in agriculture. Most consumers of limestone rely on being able to obtain raw material that meets certain specifications in terms of physical properties (crystal size) or chemical content. Special grades of high-quality white calcium oxide are used for paper coating. Calcium oxide (quicklime) is derived from limestone by calcining to expel carbon dioxide.

The following parameters were used for this design process:

Fluidized bed productivity	T/hr	10
Concentration of CaCO <sub>3</sub> in raw material (dry mass)	%	97
Moisture content of raw material	%	1.3
Moisture content of raw material at dryer outlet	%	0
Initial temperature of material	°C	15
Firing temperature	°C	900
Temperature of material at dryer outlet	°C	750
Temperature of quicklime at furnace outlet	°C	800
Temperature of quicklime at cooler outlet	°C	150
Temperature of ambient air	°C	25
Temperature of flue gases from furnace	°C	800
Temperature of gases from the dryer	°C	750
Temperature of gases from the cooler outlet	°C	150

## CHAPTER TWO

### 2.0 REVIEW OF LITERATURE

#### 2.1 Description of Various Processing Technologies

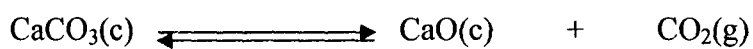
The various processing technologies used for the production of lime from pure limestone involve the use of different types of kilns such as:

- i. Shaft kilns (e.g. central burner, external chambers, beam burner, internal arch etc)
- ii. Rotary kilns (e.g. Long, Preheater, )
- iii. Other types of kilns includes the following.
  - Travelling grate
  - Top-shaped"
  - Fluidised bed furnace
  - Flash calciner
  - Rotating hearth

## 2.2 Detailed Process Description of Selected Technology

The selected technology to be used for this project is the calcinations using fluidized bed decarbonisation furnace and the descriptions of the process are as outlined below.

Lime has always been a cheap commodity because limestone deposits are readily in many sections of the country. It is produced from limestone near centres of consumption so that freight costs 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. 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 "dead-burned" 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. This lime is called "underburned" lime. The reactions involved are:



It should be noted that the volume contracts during calcinations.

As shown above, the calcinations reaction is reversible. Below 550°C, the equilibrium decomposition pressure of CO<sub>2</sub> is quite small. Between 650 and 900°C, the decomposition pressure increases rapidly and reaches 101kPa at about 900°C. In most operating furnace, the partial pressure of CO<sub>2</sub> in the gases in direct contact with the outside of the lumps is less than 900°C. The decomposition temperature at the centre of the lump is probably well above 900°C, since there the

- Burning of limestone according to size to give lump or fine lime.

Packaging of the finished lime in barrels or sheet-iron drums

### 2.3 Justification of Selected Technology

The calcination of finely divided limestone in a fluidised bed has been practiced on a relatively small scale for many years. It has several potential advantages, including:

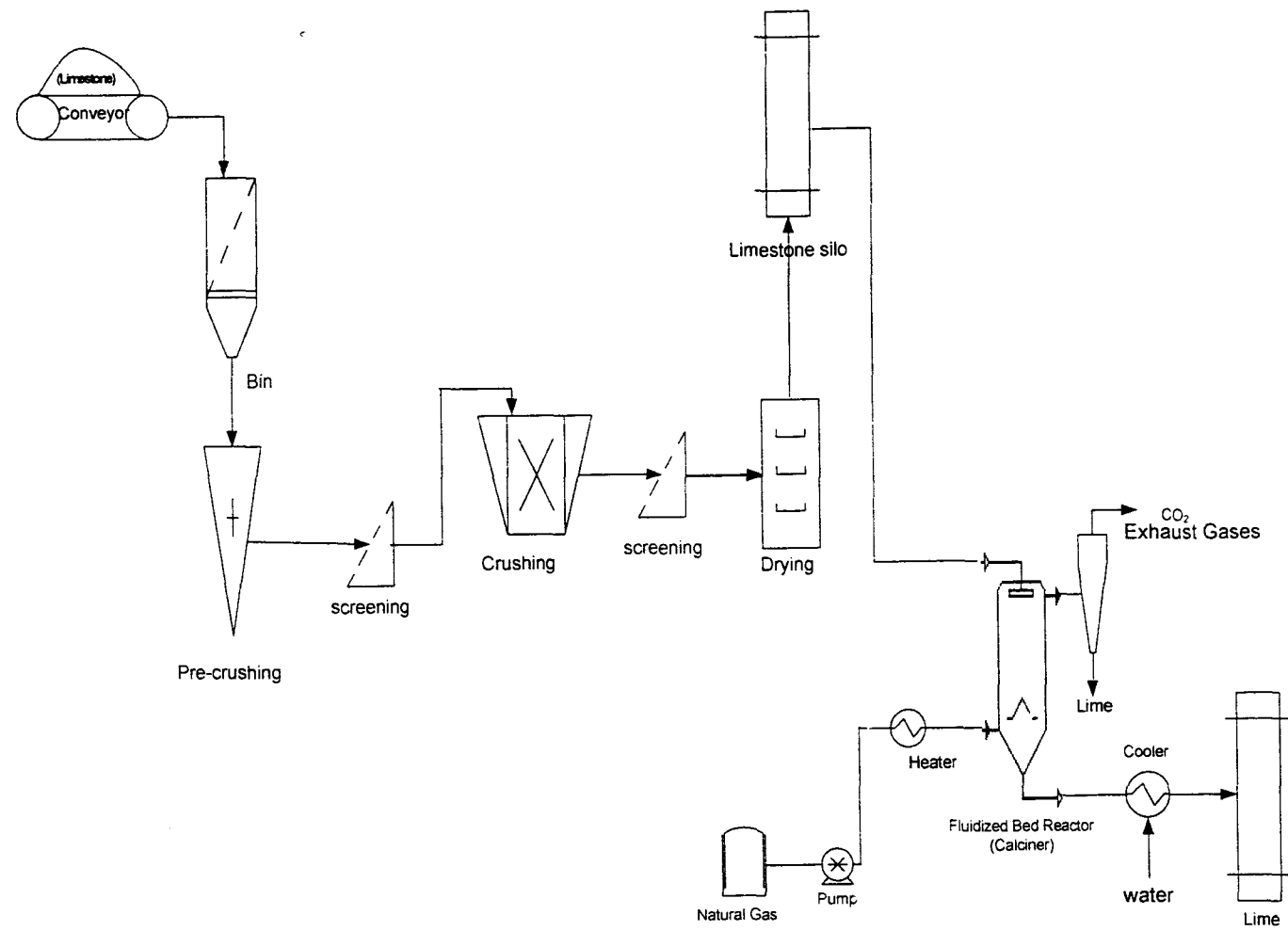
- the use of surplus grades of fine limestone,
- low NO<sub>x</sub> emissions, and
- low SO<sub>2</sub> emissions, when using high sulphur fuels.

However, the technique does not have a particularly low specific heat use, the finely divided products are not suitable for many applications and the residual calcium carbonate level is relatively high. Initial problems with using the technique for kilns with productive capacities in excess of 150 tonnes per day appear to have been resolved.

The Figure below shows the flow diagram of the fluidised bed decarbonisation plant. Fine limestone is fed to the reactor vessel and is allowed to contact a heated natural gas. The preheated limestone then enters the fluidised bed vessel where the temperature is increased and limestone starts to be calcined. As the limestone is calcined, the lighter quicklime flows over the weir wall into the bed vessel where calcination is completed. The quicklime then passes through the cooler where it is cooled by ambient air.

Although fluidised bed technology may offer lower pollutant releases than other lime kiln technologies, it is not well proven and can only produce fine lime with a high reactivity.





Flowsheet for the Production of Quicklime from Limestone

CHAPTER THREE

3.0 MATERIAL BALANCES CALCULATIONS

Basis: 100.00 kg/hr of limestone

Composition of the raw material (limestone)

Components	mass%
CaCO <sub>3</sub>	97.00
H <sub>2</sub> O	1.20
Clayey Impurities	1.80
Total	100.00

Unit 1: Conveyor

Operation: Transportation of limestone from field to bin

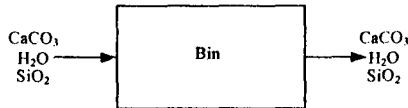


Assumption: 2% material loss during transportation

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	97.00	97.00	0.00	0.00	1.94	97.00	95.06	97.00
H <sub>2</sub> O	1.20	1.20	0.00	0.00	0.02	1.20	1.18	1.20
Clayey Impurities	1.80	1.80	0.00	0.00	0.04	1.80	1.76	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	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	2.00	100.00	98.00	100.00

Unit 2: Bin

Operation: Storage of limestone

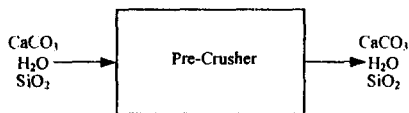


Assumption: No loss in material

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	95.06	97.00	0.00	0.00	0.00	0.00	95.06	97.00
H <sub>2</sub> O	1.18	1.20	0.00	0.00	0.00	0.00	1.18	1.20
Clayey Impurities	1.76	1.80	0.00	0.00	0.00	0.00	1.76	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	98.00	100.00	0.00	0.00	0.00	0.00	98.00	100.00

Unit 3: Pre-Crusher

Operation: Particle Size Reduction

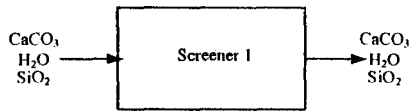


Assumption: 0.5% material loss

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	95.06	97.00	0.00	0.00	0.48	97.00	94.58	97.00
H <sub>2</sub> O	1.18	1.20	0.00	0.00	0.01	1.20	1.17	1.20
Clayey Impurities	1.76	1.80	0.00	0.00	0.01	1.80	1.76	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	98.00	100.00	0.00	0.00	0.49	100.00	97.51	100.00

**Unit 4: Screener 1**

Operation: Classification of particles into different sizes

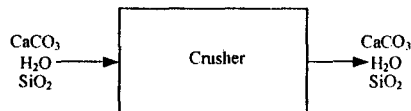


Assumption: 99% of Limestone recovered

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	94.58	97.00	0.00	0.00	0.95	97.00	93.64	97.00
H2O	1.17	1.20	0.00	0.00	0.01	1.20	1.16	1.20
Clayey Impurities	1.76	1.80	0.00	0.00	0.02	1.80	1.74	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>97.51</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.98</b>	<b>100.00</b>	<b>96.53</b>	<b>100.00</b>

**Unit 5: Crusher**

Operation: Further Reduction in the Particle Size of the Limestone

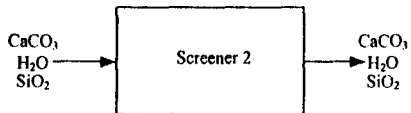


Assumption: 1.5% material loss

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	93.64	97.00	0.00	0.00	1.40	97.00	92.23	97.00
H2O	1.16	1.20	0.00	0.00	0.02	1.20	1.14	1.20
Clayey Impurities	1.74	1.80	0.00	0.00	0.03	1.80	1.71	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>96.53</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>1.45</b>	<b>100.00</b>	<b>95.09</b>	<b>100.00</b>

**Unit 6: Screener 2**

Operation: Classification of particles into different sizes

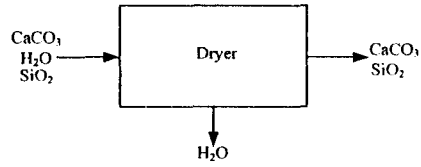


Assumption: 97.5% of Limestone recovered within the particle size range of 1-10mm

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	92.23	97.00	0.00	0.00	2.31	236.47	89.93	97.00
H2O	1.14	1.20	0.00	0.00	0.03	2.93	1.11	1.20
Clayey Impurities	1.71	1.80	0.00	0.00	0.04	4.39	1.67	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>95.09</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>2.38</b>	<b>243.79</b>	<b>92.71</b>	<b>100.00</b>

**Unit 7: Dryer**

Operation: Drying (Removal of moisture)

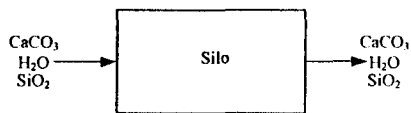


Assumption: Complete removal of moisture (water)

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	89.93	97.00	0.00	0.00	0.00	0.00	89.93	98.18
H2O	1.11	1.20	0.00	0.00	1.11	100.00	0.00	0.00
Clayey Impurities	1.67	1.80	0.00	0.00	0.00	0.00	1.67	1.82
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>92.71</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>1.11</b>	<b>100.00</b>	<b>91.60</b>	<b>100.00</b>

**Unit 8: Silo**

Operation: Storage of limestone

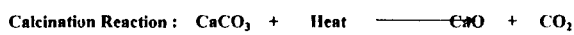
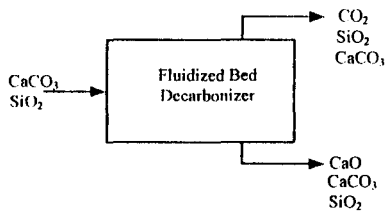


Assumption: No loss in material Storage

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	89.93	98.18	0.00	0.00	0.00	0.00	89.93	98.18
H2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	1.67	1.82	0.00	0.00	0.00	0.00	1.67	1.82
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>91.60</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>91.60</b>	<b>100.00</b>

**Unit 9: Fluidized Bed (Decarbonization) Reactor**

Process: Calcination (Decarbonization) of Limestone

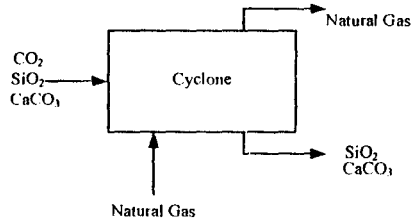


NB: The material balances around the fluidized bed reactor is based on the chemical reaction shown above

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO3	89.93	98.18	0.00	0.00	1.53	3.11	0.27	0.54
H2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	1.67	1.82	0.00	0.00	1.34	2.72	0.33	0.67
CaO	0.00	0.00	0.00	0.00	0.00	0.00	49.38	98.79
CO2	0.00	0.00	0.00	0.00	38.75	78.90	0.00	0.00
Natural Gas	0.00	0.00	50.00	100.00	7.50	15.27	0.00	0.00
<b>Total</b>	<b>91.60</b>	<b>100.00</b>	<b>50.00</b>	<b>100.00</b>	<b>49.11</b>	<b>100.00</b>	<b>49.98</b>	<b>100.00</b>

**Unit 10: Cyclone**

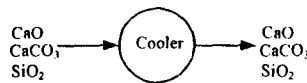
Operation: Separation of the Lime Particles and Impurity from the Gases



Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	1.53	3.11	0.00	0.00	1.15	25.71	0.38	0.86
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	1.34	2.72	0.00	0.00	1.00	22.45	0.33	0.75
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	38.75	78.90	0.00	0.00	1.94	43.44	36.81	82.44
Natural Gas	7.50	15.27	0.00	0.00	0.38	8.41	7.13	15.96
<b>Total</b>	<b>49.11</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>4.46</b>	<b>100.00</b>	<b>44.65</b>	<b>100.00</b>

**Unit 11: Cooler**

Operation: Reducing the temperature of the final product (Quicklime)



Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	0.27	0.54	0.00	0.00	0.00	0.00	0.27	0.54
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	0.33	0.67	0.00	0.00	0.00	0.00	0.33	0.67
CaO	49.38	98.79	0.00	0.00	0.00	0.00	49.38	98.79
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>49.98</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>49.98</b>	<b>100.00</b>

**Calculation of scale factor**

Molecular weights of the components

Component	kg/kgmol
CaCO <sub>3</sub>	100.09
H <sub>2</sub> O	18.00
Clayey Impurities	60.09
CaO	56.08
CO <sub>2</sub>	44.01

Conversion factor: 1.00 ton/hr = 1016.05 kg/hr

Quicklime 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, Quicklime produced from the basis (100kg/hr) = 49.98 kg/hr

In other words, the final output = 49.98 kg/hr

The scale-up factor = 203.28

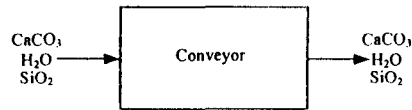
The scale up factor will be used to scale up the masses of the different components in each unit.

SCALED UP MATERIAL BALANCES (Scaling up to capacity of 10 tons/hr)

Unit 1: Conveyor

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

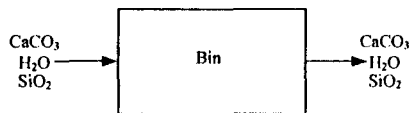
Assumption: 98% material recovery (2% loss)



Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	19718.28	97.00	0.00	0.00	394.37	97.00	19323.92	97.00
H <sub>2</sub> O	243.94	1.20	0.00	0.00	4.88	1.20	239.06	1.20
Impurities	365.91	1.80	0.00	0.00	7.32	1.80	358.59	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>20328.13</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>406.56</b>	<b>100.00</b>	<b>19921.57</b>	<b>100.00</b>

Unit 2: Bin

Operation: Storage of limestone

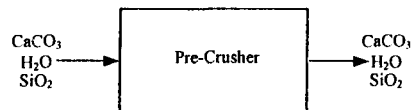


Assumption: No loss in material

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	19323.92	97.00	0.00	0.00	0.00	0.00	19323.92	97.00
H <sub>2</sub> O	239.06	1.20	0.00	0.00	0.00	0.00	239.06	1.20
Clayey Impurities	358.59	1.80	0.00	0.00	0.00	0.00	358.59	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>19921.57</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>19921.57</b>	<b>100.00</b>

Unit 3: Pre-Crusher

Operation: Particle Size Reduction

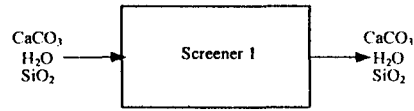


Assumption: 0.5% material loss

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	19323.92	97.00	0.00	0.00	96.62	97.00	19227.30	97.00
H <sub>2</sub> O	239.06	1.20	0.00	0.00	1.20	1.20	237.86	1.20
Clayey Impurities	358.59	1.80	0.00	0.00	1.79	1.80	356.80	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>19921.57</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>99.61</b>	<b>100.00</b>	<b>19821.96</b>	<b>100.00</b>

**Unit 4: Screener 1**

Operation: Classification of particles into different sizes

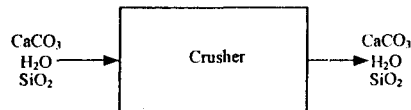


Assumption: 99% of Limestone recovered within the screen size range of 10-50mm diameter

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	19227.30	97.00	0.00	0.00	192.27	97.00	19035.03	97.00
H <sub>2</sub> O	237.86	1.20	0.00	0.00	2.38	1.20	235.48	1.20
Clayey Impurities	356.80	1.80	0.00	0.00	3.57	1.80	353.23	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>19821.96</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>198.22</b>	<b>100.00</b>	<b>19623.74</b>	<b>100.00</b>

**Unit 5: Crusher**

Operation: Further Reduction in the Particle Size of the Limestone

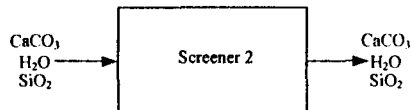


Assumption: 1.5% material loss

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	19035.03	97.00	0.00	0.00	285.53	97.00	18749.50	97.00
H <sub>2</sub> O	235.48	1.20	0.00	0.00	3.53	1.20	231.95	1.20
Clayey Impurities	353.23	1.80	0.00	0.00	5.30	1.80	347.93	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>19623.74</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>294.36</b>	<b>100.00</b>	<b>19329.38</b>	<b>100.00</b>

**Unit 6: Screener 2**

Operation: Classification of particles into different sizes

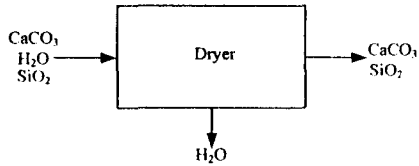


Assumption: 97.5% of Limestone recovered within the particle size range of 1-10mm diameter

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	18749.50	97.00	0.00	0.00	468.74	97.00	18280.76	97.00
H <sub>2</sub> O	231.95	1.20	0.00	0.00	5.80	1.20	226.15	1.20
Clayey Impurities	347.93	1.80	0.00	0.00	8.70	1.80	339.23	1.80
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>19329.38</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>483.23</b>	<b>100.00</b>	<b>18846.15</b>	<b>100.00</b>

**Unit 7: Dryer**

Operation: Drying (Removal of moisture)



Assumption: Complete removal of moisture (water)

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	18280.76	97.00	0.00	0.00	0.00	0.00	18280.76	98.18
H <sub>2</sub> O	226.15	1.20	0.00	0.00	226.15	100.00	0.00	0.00
Clayey Impurities	339.23	1.80	0.00	0.00	0.00	0.00	339.23	1.82
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>18846.15</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>226.15</b>	<b>100.00</b>	<b>18619.99</b>	<b>100.00</b>

**Unit 8: Silo**

Operation: Storage of limestone

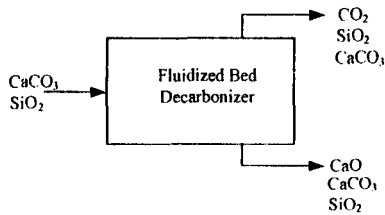


Assumption: No loss in material Storage

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	18280.76	98.18	0.00	0.00	0.00	0.00	18280.76	98.18
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	339.23	1.82	0.00	0.00	0.00	0.00	339.23	1.82
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>18619.99</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>18619.99</b>	<b>100.00</b>

**Unit 9: Fluidized Bed (Decarbonization) Reactor**

Process: Calcination (Decarbonization) of Limestone



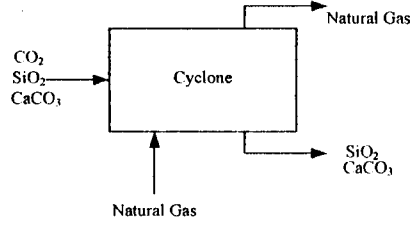
NB: The material balances around the fluidized bed reactor is based on the chemical reaction shown above

Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	18280.76	98.18	0.00	0.00	310.77	3.11	54.84	0.54
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	339.23	1.82	0.00	0.00	271.38	2.72	67.85	0.67
CaO	0.00	0.00	0.00	0.00	0.00	0.00	10037.78	98.79
CO <sub>2</sub>	0.00	0.00	0.00	0.00	7877.37	78.90	0.00	0.00
Natural Gas	0.00	0.00	10164.06	100.00	1524.61	15.27	0.00	0.00
<b>Total</b>	<b>18619.99</b>	<b>100.00</b>	<b>10164.06</b>	<b>100.00</b>	<b>9984.13</b>	<b>100.00</b>	<b>10160.47</b>	<b>100.00</b>



**Unit 10: Cyclone**

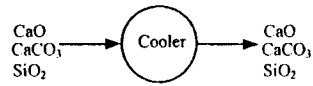
Operation: Separation of the Lime Particles and Impurity from the Gases



Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	310.77	3.11	0.00	0.00	233.08	25.71	77.69	0.86
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	271.38	2.72	0.00	0.00	203.54	22.45	67.85	0.75
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	7877.37	78.90	0.00	0.00	393.87	43.44	7483.50	82.44
Natural Gas	1524.61	15.27	0.00	0.00	76.23	8.41	1448.38	15.96
<b>Total</b>	<b>9984.13</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>906.72</b>	<b>100.00</b>	<b>9077.42</b>	<b>100.00</b>

**Unit 11: Cooler**

Operation: Reducing the temperature of the final product (Quicklime)



Components	IN				OUT			
	Input		Added		Loss		Output	
	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%	mass (kg/hr)	mass%
CaCO <sub>3</sub>	54.84	0.54	0.00	0.00	0.00	0.00	54.84	0.54
H <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clayey Impurities	67.85	0.67	0.00	0.00	0.00	0.00	67.85	0.67
CaO	10037.78	98.79	0.00	0.00	0.00	0.00	10037.78	98.79
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	<b>10160.47</b>	<b>100.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>10160.47</b>	<b>100.00</b>

**Final product (Quicklime):**

Components	mass (kg/hr)	mass%
CaCO <sub>3</sub>	54.84	0.54
H <sub>2</sub> O	0.00	0.00
Impurities	67.85	0.67
CaO	10037.78	98.79
CO <sub>2</sub>	0.00	0.00
<b>Total</b>	<b>10160.47</b>	<b>100.00</b>

## CHAPTER FOUR

### 4.0 ENERGY BALANCES

#### 4.1 ENERGY BALANCES CALCULATIONS

$$M_w := \begin{pmatrix} 100.090 \\ 18.016 \\ 60.000 \\ 56.080 \\ 44.010 \\ 16.040 \end{pmatrix} \cdot \frac{\text{kg}}{\text{kmole}} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

Heat Capacity Coefficient :

$$\text{Heat}_{\text{coeff}} := \begin{pmatrix} 82.34 & 4.975 \cdot 10^{-2} & -12.87 \cdot 10^5 & 0 \\ 18.2964 & 47.212 \cdot 10^{-2} & -133.88 \cdot 10^{-5} & 1314.2 \cdot 10^{-9} \\ 15.2 & 2.68 \cdot 10^{-2} & 0 & 0 \\ 41.84 & 2.03 \cdot 10^{-2} & -4.52 \cdot 10^5 & 0 \\ 36.11 & 4.233 \cdot 10^{-2} & -2.887 \cdot 10^{-5} & 7.464 \cdot 10^{-9} \\ 19.87 & 5.021 \cdot 10^{-2} & 1.268 \cdot 10^{-5} & -11.0 \cdot 10^{-9} \end{pmatrix} \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

(Himmelblau, 1996)

$$a := \frac{\text{Heat}_{\text{coeff}}^{(1)}}{M_w \cdot \frac{\text{kmole}}{\text{kg}}} \quad b := \frac{\text{Heat}_{\text{coeff}}^{(2)}}{M_w \cdot \frac{\text{kmole}}{\text{kg}}} \quad c := \frac{\text{Heat}_{\text{coeff}}^{(3)}}{M_w \cdot \frac{\text{kmole}}{\text{kg}}} \quad d := \frac{\text{Heat}_{\text{coeff}}^{(4)}}{M_w \cdot \frac{\text{kmole}}{\text{kg}}}$$

coeffs := augment(a, b, c, d)

$$\text{coeffs} = \begin{pmatrix} 0.823 & 4.971 \times 10^{-4} & -1.286 \times 10^4 & 0 \\ 1.016 & 0.026 & -7.431 \times 10^{-5} & 7.295 \times 10^{-8} \\ 0.253 & 4.467 \times 10^{-4} & 0 & 0 \\ 0.746 & 3.62 \times 10^{-4} & -8.06 \times 10^3 & 0 \\ 0.82 & 9.618 \times 10^{-4} & -6.56 \times 10^{-7} & 1.696 \times 10^{-10} \\ 1.239 & 3.13 \times 10^{-3} & 7.905 \times 10^{-7} & -6.858 \times 10^{-10} \end{pmatrix}$$

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

$$a = \begin{pmatrix} 0.823 \\ 1.016 \\ 0.253 \\ 0.746 \\ 0.82 \\ 1.239 \end{pmatrix} \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \quad b = \begin{pmatrix} 4.971 \times 10^{-4} \\ 0.026 \\ 4.467 \times 10^{-4} \\ 3.62 \times 10^{-4} \\ 9.618 \times 10^{-4} \\ 3.13 \times 10^{-3} \end{pmatrix} \frac{\text{kJ}}{\text{kg} \cdot \text{K}^2} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

$$c = \begin{pmatrix} -1.286 \times 10^4 \\ -7.431 \times 10^{-5} \\ 0 \\ -8.06 \times 10^3 \\ -6.56 \times 10^{-7} \\ 7.905 \times 10^{-7} \end{pmatrix} \frac{\text{kJ}}{\text{kg} \cdot \text{K}^3} \quad d = \begin{pmatrix} 0 \\ 7.295 \times 10^{-8} \\ 0 \\ 0 \\ 1.696 \times 10^{-10} \\ -6.858 \times 10^{-10} \end{pmatrix} \frac{\text{kJ}}{\text{kg} \cdot \text{K}^4}$$

$$\begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

**Heat of Formation ( $H_f$ ) :**

$$H_f := \begin{pmatrix} -1206.90 \\ -285.840 \\ -851.00 \\ -635.60 \\ -393.51 \\ -74.84 \end{pmatrix} \cdot 10^3 \cdot \frac{\text{kJ}}{\text{kmole}}$$

$$\begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

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

$$H_f = \begin{pmatrix} -1.206 \times 10^4 \\ -1.587 \times 10^4 \\ -1.418 \times 10^4 \\ -1.133 \times 10^4 \\ -8.941 \times 10^3 \\ -4.666 \times 10^3 \end{pmatrix} \frac{\text{kJ}}{\text{kg}}$$

$$\begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### 4.1.1 ENERGY BALANCES AROUND THE BIN

The energy balances of the bin will be calculated using

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

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 AROUND THE BIN

Given the mass and Initial temperatures of the materials at Inlet :

$$m' := \begin{pmatrix} 19323.92 \\ 239.06 \\ 358.59 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{in}} := \begin{bmatrix} 15 \\ 15 \\ 15 \\ 15 \\ 15 \\ 15 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_1} = 288.15 \text{ K}$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}} \quad \Delta T_1 = -10 \text{ K}$$

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

$$c_1 = -1.286 \times 10^4 \frac{\text{kJ}}{\text{kg} \cdot \text{K}^3}$$

$$b_1 = 4.971 \times 10^{-4} \frac{\text{kJ}}{\text{kg} \cdot \text{K}^2}$$

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

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right]$$

$$C_{p1} = -1.068 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$Q_{\text{limestone}} = 2.063 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 288.15 \text{ K}$

$$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}} \quad \Delta T_2 = -10 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right]$$

$$C_{p2} = 4.142 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$$

$$Q_{\text{water}} = -9.901 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Clayey impurities (SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 288.15 \text{ K}$

$$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}} \quad \Delta T_3 = -10 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right] \quad C_{p3} = 0.382 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \quad Q_{\text{impure}} = -1.37 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 288.15 \text{ K}$

$$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}} \quad \Delta T_4 = -10 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right] \quad C_{p4} = -6.692 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 288.15 \text{ K}$

$$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}} \quad \Delta T_5 = -10 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right] \quad C_{p5} = 1.047 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \quad Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 288.15 \text{ K}$

$$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}} \qquad \Delta T_6 = -10 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_6 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right] \qquad C_{p6} = 2.19 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \qquad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Input:

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = 2.063 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### ENERGY OUTPUT AROUND THE BIN

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 19323.92 \\ 239.06 \\ 358.59 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \qquad \text{and} \qquad T_{\text{out}} := \begin{pmatrix} 19 \\ 19 \\ 19 \\ 19 \\ 19 \\ 19 \end{pmatrix} + 273.15 \cdot \text{K} \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural} \cdot \text{Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 292.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \qquad \Delta T_1 = -6 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \qquad C_{p1} = -1.097 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \qquad Q_{\text{limestone}} = 1.272 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 292.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}}$$

$$\Delta T_2 = -6 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right]$$

$$C_{p2} = 4.148 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$$

$$Q_{\text{water}} = -5.95 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_3} = 292.15 \text{ K}$$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}}$$

$$\Delta T_3 = -6 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right]$$

$$C_{p3} = 0.384 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = -825.819 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_4} = 292.15 \text{ K}$$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}}$$

$$\Delta T_4 = -6 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right]$$

$$C_{p4} = -6.879 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_5} = 292.15 \text{ K}$$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}}$$

$$\Delta T_5 = -6 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right]$$

$$C_{p5} = 1.05 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

## Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Outlet temperature:  $T_{out_5} = 292.15 K$

$$\Delta T_6 := T_{out_6} - T_{ref} \qquad \Delta T_6 = -6 K$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{out_6} + c_5 \cdot (T_{out_6})^2 + d_6 \cdot (T_{out_6})^3 \right] \qquad C_{p6} = 2.08 \frac{kJ}{kg \cdot K}$$

$$Q_{Natural.Gas} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \qquad Q_{Natural.Gas} = 0 \frac{kJ}{hr}$$

### Total energy Output :

$$Q_{out} := Q_{limestone} + Q_{water} + Q_{impure} + Q_{quicklime} + Q_{carbondioxide} + Q_{Natural.Gas}$$

### HEAT LOAD ON THE BIN:

$$Q_{out} = 1.272 \times 10^{14} \frac{kJ}{hr}$$

$$Q_{Bin} := Q_{in} - Q_{out}$$

$$Q_{Bin} = 7.906 \times 10^{13} \frac{kJ}{hr}$$

## 4.1.2 ENERGY BALANCES AROUND THE PRE-CRUSHER

The energy balances of the crusher will be calculated using

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

where

$$m = \text{"mass"}$$

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

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

### ENERGY INPUT AROUND THE PRE-CRUSHER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19323.92 \\ 239.06 \\ 358.59 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{in} := \begin{pmatrix} 19 \\ 19 \\ 19 \\ 19 \\ 19 \\ 19 \end{pmatrix} + 273.15 \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ Impurities \\ CaO \\ CO_2 \\ Natural \cdot Gas \end{pmatrix}$$



### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_1} = 292.15 \text{ K}$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}} \qquad \Delta T_1 = -6 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right] \qquad C_{p1} = -1.097 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \qquad Q_{\text{limestone}} = 1.272 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 292.15 \text{ K}$

$$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}} \qquad \Delta T_2 = -6 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right] \qquad C_{p2} = 4.148 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \qquad Q_{\text{water.}} = -5.95 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{out}_3} = 292.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}} \qquad \Delta T_3 = -6 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right] \qquad C_{p3} = 0.384 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \qquad Q_{\text{impure}} = -825.819 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 292.15 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}} \qquad \Delta T_4 = -6 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right] \qquad C_{p4} = -6.879 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

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

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{in}_5} = 292.15 \text{ K}$

$$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}} \qquad \Delta T_5 = -6 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right] \qquad C_{p5} = 1.05 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \qquad Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_6} = 292.15 \text{ K}$

$$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}} \qquad \Delta T_6 = -6 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_5 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right] \qquad C_{p6} = 2.08 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \qquad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Input :

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = 1.272 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## ENERGY OUTPUT AROUND THE PRE-CRUSHER

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 19227.30 \\ 237.86 \\ 356.80 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{pmatrix} 30 \\ 30 \\ 30 \\ 30 \\ 30 \\ 30 \end{pmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 303.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \quad \Delta T_1 = 5 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \quad C_{p1} = -1.182 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -1.136 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 303.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}} \quad \Delta T_2 = 5 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right] \quad C_{p2} = 4.163 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water}} = 4.951 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities (SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 303.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}} \quad \Delta T_3 = 5 \text{ K}$$

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

$$C_{p3} = 0.389 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 693.513 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_4} = 303.15 \text{ K}$

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

$$\Delta T_4 = 5 \text{ K}$$

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

$$C_{p4} = -7.407 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_5} = 303.15 \text{ K}$

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

$$\Delta T_5 = 5 \text{ K}$$

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

$$C_{p5} = 1.057 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_6} = 303.15 \text{ K}$

$$\Delta T_6 := T_{out_6} - T_{\text{ref}}$$

$$\Delta T_6 = 5 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{out_6} + c_5 \cdot (T_{out_6})^2 + d_6 \cdot (T_{out_6})^3 \right]$$

$$C_{p6} = 2.108 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6$$

$$Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

## Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -1.136 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## HEAT LOAD ON THE PRE-CRUSHER:

$$Q_{\text{Pre.crusher}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Pre.crusher}} = 2.408 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### 4.1.3 ENERGY BALANCES AROUND THE SCREENER 1

The energy balances of the screener will be calculated using

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

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

$$\Delta T = T_{\text{in}} - T_{\text{ref}}$$

### ENERGY INPUT AROUND THE SCREENER 1

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19227.30 \\ 237.86 \\ 356.80 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{in}} := \begin{bmatrix} 30 \\ 30 \\ 30 \\ 30 \\ 30 \\ 30 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_1} = 303.15 \text{ K}$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}}$$

$$\Delta T_1 = 5 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right]$$

$$C_{p1} = -1.182 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$Q_{\text{limestone}} = -1.136 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 303.15 \text{ K}$

$$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}} \quad \Delta T_2 = 5 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right] \quad C_{p2} = 4.163 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water.}} = 4.951 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Impurities (SiO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 303.15 \text{ K}$

$$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}} \quad \Delta T_3 = 5 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right] \quad C_{p3} = 0.389 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \quad Q_{\text{impure}} = 693.513 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 303.15 \text{ K}$

$$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}} \quad \Delta T_4 = 5 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right] \quad C_{p4} = -7.407 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 303.15 \text{ K}$

$$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}} \quad \Delta T_5 = 5 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right] \quad C_{p5} = 1.057 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_6} = 303.15 \text{ K}$

$$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}}$$

$$\Delta T_6 = 5 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_6 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right]$$

$$C_{p6} = 2.241 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6$$

$$Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy in:

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = -1.136 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## ENERGY OUTPUT AROUND THE SCREENER 1

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 19035.03 \\ 235.48 \\ 353.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{pmatrix} 34 \\ 34 \\ 34 \\ 34 \\ 34 \\ 34 \end{pmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 307.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}}$$

$$\Delta T_1 = 9 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right]$$

$$C_{p1} = -1.213 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$Q_{\text{limestone}} = -2.078 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 307.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}}$$

$$\Delta T_2 = 9 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right]$$

$$C_{p2} = 4.168 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$$

$$Q_{\text{water.}} = 8.833 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 307.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}}$$

$$\Delta T_3 = 9 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right]$$

$$C_{p3} = 0.391 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 1.242 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_4} = 307.15 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}}$$

$$\Delta T_4 = 9 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right]$$

$$C_{p4} = -7.604 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_5} = 307.15 \text{ K}$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}}$$

$$\Delta T_5 = 9 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right]$$

$$C_{p5} = 1.059 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$



### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Inlet temperature:  $T_{out_6} = 307.15 K$

$$\Delta T_6 := T_{out_6} - T_{ref} \qquad \Delta T_6 = 9 K$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{in_6} + c_6 \cdot (T_{in_6})^2 + d_6 \cdot (T_{in_6})^3 \right] \qquad C_{p6} = 2.241 \frac{kJ}{kg \cdot K}$$

$$Q_{Natural.Gas} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \qquad Q_{Natural.Gas} = 0 \frac{kJ}{hr}$$

### Total energy out:

$$Q_{in} := Q_{limestone} + Q_{water} + Q_{impure} + Q_{quicklime} + Q_{carbondioxide} + Q_{Natural.Gas}$$

$$Q_{out} = -1.136 \times 10^{14} \frac{kJ}{hr}$$

### HEAT LOAD ON SCREENER 1:

$$Q_{Screener.1} := Q_{in} - Q_{out}$$

$$Q_{Screener.1} = -9.422 \times 10^{13} \frac{kJ}{hr}$$

## 4.1.4 ENERGY BALANCES AROUND THE CRUSHER

The energy balances of the crusher will be calculated using

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

where

$$m = \text{"mass"}$$

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

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

### ENERGY INPUT AROUND THE CRUSHER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 19035.03 \\ 235.48 \\ 353.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{kg}{hr} \qquad \text{and} \qquad T_{in} := \begin{pmatrix} 34 \\ 34 \\ 34 \\ 34 \\ 34 \\ 34 \end{pmatrix} + 273.15 \cdot K \qquad \begin{pmatrix} CaCO_3 \\ H_2O \\ Impurities \\ CaO \\ CO_2 \\ Natural \cdot Gas \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_1} = 307.15 \text{ K}$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}} \qquad \Delta T_1 = 9 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right] \qquad C_{p1} = -1.213 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \qquad Q_{\text{limestone}} = -2.078 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 307.15 \text{ K}$

$$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}} \qquad \Delta T_2 = 9 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right] \qquad C_{p2} = 4.168 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \qquad Q_{\text{water.}} = 8.833 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities (SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 307.15 \text{ K}$

$$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}} \qquad \Delta T_3 = 9 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right] \qquad C_{p3} = 0.391 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \qquad Q_{\text{impure}} = 1.242 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 307.15 \text{ K}$

$$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}} \qquad \Delta T_4 = 9 \text{ K}$$

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

$$C_{p4} = -7.694 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Inlet temperature: } T_{in_5} = 307.15 \text{ K}$$

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

$$\Delta T_5 = 9 \text{ K}$$

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

$$C_{p5} = 1.059 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Inlet temperature: } T_{in_6} = 307.15 \text{ K}$$

$$\Delta T_6 := T_{in_6} - T_{\text{ref}}$$

$$\Delta T_6 = 9 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{in_6} + c_6 \cdot (T_{in_6})^2 + d_6 \cdot (T_{in_6})^3 \right]$$

$$C_{p6} = 2.118 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6$$

$$Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Input :

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = -4.988 \times 10^{15} \frac{\text{kJ}}{\text{day}}$$

## ENERGY OUTPUT AROUND THE CRUSHER

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 18749.50 \\ 231.95 \\ 347.93 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{bmatrix} 42 \\ 42 \\ 42 \\ 42 \\ 42 \\ 42 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 315.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \quad \Delta T_1 = 17 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \quad C_{p1} = -1.277 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -4.071 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 315.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}} \quad \Delta T_2 = 17 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right] \quad C_{p2} = 4.177 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water.}} = 1.647 \times 10^4 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 315.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}} \quad \Delta T_3 = 17 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{out_3} + c_3 \cdot (T_{out_3})^2 + d_3 \cdot (T_{out_3})^3 \right] \quad C_{p3} = 0.394 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \quad Q_{\text{impure}} = 2.331 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

$$\text{Reference temperature:} \quad T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature:} \quad T_{out_4} = 315.15 \text{ K}$$

$$\Delta T_4 := T_{out_4} - T_{\text{ref}} \quad \Delta T_4 = 17 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{out_4} + c_4 \cdot (T_{out_4})^2 + d_4 \cdot (T_{out_4})^3 \right] \quad C_{p4} = -8.005 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

$$\text{Reference temperature:} \quad T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature:} \quad T_{out_5} = 315.15 \text{ K}$$

$$\Delta T_5 := T_{out_5} - T_{\text{ref}} \quad \Delta T_5 = 17 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{out_5} + c_5 \cdot (T_{out_5})^2 + d_5 \cdot (T_{out_5})^3 \right] \quad C_{p5} = 1.064 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\Delta H_{\text{carbodioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \quad Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

$$\text{Reference temperature:} \quad T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature:} \quad T_{out_6} = 315.15 \text{ K}$$

$$\Delta T_6 := T_{out_6} - T_{\text{ref}} \quad \Delta T_6 = 17 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{out_6} + c_6 \cdot (T_{out_6})^2 + d_6 \cdot (T_{out_6})^3 \right] \quad C_{p6} = 2.139 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}} \quad Q_{\text{out}} = -4.071 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## HEAT LOAD ON THE CRUSHER:

$$Q_{\text{Crusher}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Crusher}} = 1.992 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### 4.1.5 ENERGY BALANCES AROUND THE SCREENER 2

The energy balances of the screener will be calculated using

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

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

$$\Delta T = T_{\text{in}} - T_{\text{ref}}$$

### ENERGY INPUT AROUND THE SCREENER 2

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 18749.50 \\ 231.95 \\ 347.93 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{in}} := \begin{bmatrix} 42 \\ 42 \\ 42 \\ 42 \\ 42 \\ 42 \end{bmatrix} + 273.15 \cdot \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{K impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate ( $\text{CaCO}_3$ ) in the inlet

Reference temperature:

$$T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

Inlet temperature:

$$T_{\text{in}_1} = 315.15 \text{ K}$$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}}$$

$$\Delta T_1 = 17 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right]$$

$$C_{p1} = -1.277 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$Q_{\text{limestone}} = -4.071 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

#### Energy of moisture ( $\text{H}_2\text{O}$ ) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 315.15 \text{ K}$

$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}}$   $\Delta T_2 = 17 \text{ K}$

$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right]$   $C_{p2} = 4.177 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$   $Q_{\text{water}} = 1.647 \times 10^4 \frac{\text{kJ}}{\text{hr}}$

### Energy of Impurities (SiO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 315.15 \text{ K}$

$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}}$   $\Delta T_3 = 17 \text{ K}$

$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right]$   $C_{p3} = 0.394 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$   $Q_{\text{impure}} = 2.331 \times 10^3 \frac{\text{kJ}}{\text{hr}}$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 315.15 \text{ K}$

$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}}$   $\Delta T_4 = 17 \text{ K}$

$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right]$   $C_{p4} = -8.005 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$   $Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 315.15 \text{ K}$

$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}}$   $\Delta T_5 = 17 \text{ K}$

$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right]$   $C_{p5} = 1.064 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_6} = 315.15 \text{ K}$

$$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}} \quad \Delta T_6 = 17 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_6 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right] \quad C_{p6} = 2.282 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{day}}$$

### Total energy in:

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = -4.071 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## ENERGY OUTPUT AROUND THE SCREENER 2

Given the mass and temperatures of the output as

$$m' := \begin{pmatrix} 18280.76 \\ 226.15 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{bmatrix} 46 \\ 46 \\ 46 \\ 46 \\ 46 \\ 46 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 319.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \quad \Delta T_1 = 21 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \quad C_{p1} = -1.31 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -5.028 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$



Outlet temperature:  $T_{\text{out}_2} = 319.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}}$$

$$\Delta T_2 = 21 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right]$$

$$C_{p2} = 4.181 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$$

$$Q_{\text{water.}} = 1.986 \times 10^4 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 319.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}}$$

$$\Delta T_3 = 21 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right]$$

$$C_{p3} = 0.396 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 2.82 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_4} = 319.15 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}}$$

$$\Delta T_4 = 21 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right]$$

$$C_{p4} = -8.21 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_5} = 319.15 \text{ K}$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}}$$

$$\Delta T_5 = 21 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right]$$

$$C_{p5} = 1.066 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{out}_6} = 319.15 \text{ K}$

$$\Delta T_6 := T_{\text{out}_6} - T_{\text{ref}} \quad \Delta T_6 = 21 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_6 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right] \quad C_{p6} = 2.282 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy out:

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -5.028 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### HEAT LOAD ON THE SCREENER 2 :

$$Q_{\text{Screener.2}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Screener.2}} = 9.573 \times 10^{13} \frac{\text{kJ}}{\text{hr}}$$

## 4.1.6 ENERGY BALANCES AROUND THE DRYER

The energy balances of the dryer will be calculated using

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

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  $\Delta T = T_{\text{in}} - T_{\text{ref}}$

## ENERGY INPUT AROUND THE DRYER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 18280.76 \\ 226.15 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{in}} := \begin{pmatrix} 46 \\ 46 \\ 46 \\ 46 \\ 46 \\ 46 \end{pmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_1} = 319.15 \text{ K}$

$$\Delta T_1 := T_{\text{in}_1} - T_{\text{ref}} \quad \Delta T_1 = 21 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{in}_1} + c_1 \cdot (T_{\text{in}_1})^2 + d_1 \cdot (T_{\text{in}_1})^3 \right] \quad C_{p1} = -1.31 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -5.028 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_2} = 319.15 \text{ K}$

$$\Delta T_2 := T_{\text{in}_2} - T_{\text{ref}} \quad \Delta T_2 = 21 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{in}_2} + c_2 \cdot (T_{\text{in}_2})^2 + d_2 \cdot (T_{\text{in}_2})^3 \right] \quad C_{p2} = 4.181 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water}} = 1.986 \times 10^4 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 319.15 \text{ K}$

$$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}} \quad \Delta T_3 = 21 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right] \quad C_{p3} = 0.396 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \quad Q_{\text{impure}} = 2.82 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 319.15 \text{ K}$

$$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}} \quad \Delta T_4 = 21 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right] \quad C_{p4} = -8.21 \times 10^8 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 319.15 \text{ K}$

$$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}} \quad \Delta T_5 = 21 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right] \quad C_{p5} = 1.066 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \quad Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_6} = 319.15 \text{ K}$

$$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}} \quad \Delta T_6 = 21 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_6 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right] \quad C_{p6} = 2.149 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Input :

$$Q_{\text{in}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{in}} = -5.028 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

## ENERGY OUTPUT AROUND THE DRYER

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 18280.76 \\ 0.00 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{pmatrix} 750 \\ 750 \\ 750 \\ 750 \\ 750 \\ 750 \end{pmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}}$$

$$\Delta T_1 = 725 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right]$$

$$C_{p1} = -1.346 \times 10^{10} \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1$$

$$Q_{\text{limestone}} = -5.028 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}}$$

$$\Delta T_2 = 725 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right]$$

$$C_{p2} = 28.166 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2$$

$$Q_{\text{water.}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities (SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}}$$

$$\Delta T_3 = 725 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right]$$

$$C_{p3} = 0.71 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 1.747 \times 10^5 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_4} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}} \quad \Delta T_4 = 725 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right] \quad C_{p4} = -8.437 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_5} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}} \quad \Delta T_5 = 725 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right] \quad C_{p5} = 1.3 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \quad Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_6} = 1.023 \times 10^3 \text{ K}$

$$\Delta T_6 := T_{\text{out}_6} - T_{\text{ref}} \quad \Delta T_6 = 725 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{out}_6} + c_6 \cdot (T_{\text{out}_6})^2 + d_6 \cdot (T_{\text{out}_6})^3 \right] \quad C_{p6} = 3.02 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -1.784 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

### HEAT LOAD ON THE DRYER:

$$Q_{\text{Dryer}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Dryer}} = 1.779 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

#### 4.1.7 ENERGY BALANCES AROUND THE FLUIDIZED BED DECARBONIZATION FURNACE

The energy balances of the fluidized bed decarbonization furnace will be calculated using

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

where

$$m = \text{"mass"}$$

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

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

#### ENERGY INPUT AROUND THE FLUIDIZED BED DECARBONIZER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 18280.76 \\ 0.00 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{in} := \begin{bmatrix} 750 \\ 750 \\ 750 \\ 750 \\ 750 \\ 900 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

$$\text{Reference temperature:} \quad T_{ref} := (25 + 273.15) \cdot \text{K}$$

$$\text{Inlet temperature:} \quad T_{in_1} = 1.023 \times 10^3 \text{ K}$$

$$\Delta T_1 := T_{in_1} - T_{ref} \quad \Delta T_1 = 725 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{in_1} + c_1 \cdot (T_{in_1})^2 + d_1 \cdot (T_{in_1})^3 \right] \quad C_{p1} = -1.346 \times 10^{10} \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot \left[ C_{p1} \cdot \Delta T_1 + H_{f_1} \right] \quad Q_{\text{limestone}} = -1.784 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

#### Energy of moisture (H<sub>2</sub>O) in the inlet

$$\text{Reference temperature:} \quad T_{ref} := (25 + 273.15) \cdot \text{K}$$

$$\text{Inlet temperature:} \quad T_{in_2} = 1.023 \times 10^3 \text{ K}$$

$$\Delta T_2 := T_{in_2} - T_{ref} \quad \Delta T_2 = 725 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{in_2} + c_2 \cdot (T_{in_2})^2 + d_2 \cdot (T_{in_2})^3 \right] \quad C_{p2} = 28.166 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water}} := m'_2 \cdot \left[ C_{p2} \cdot \Delta T_2 + H_{f_2} \right] \quad Q_{\text{water}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_3} = 1.023 \times 10^3 \text{ K}$

$\Delta T_3 := T_{\text{in}_3} - T_{\text{ref}}$   $\Delta T_3 = 725 \text{ K}$

$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{in}_3} + c_3 \cdot (T_{\text{in}_3})^2 + d_3 \cdot (T_{\text{in}_3})^3 \right]$   $C_{p3} = 0.71 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{impure}} := m'_3 \cdot \left[ C_{p3} \cdot \Delta T_3 + H_{f_3} \right]$   $Q_{\text{impure}} = -4.637 \times 10^6 \frac{\text{kJ}}{\text{hr}}$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_4} = 1.023 \times 10^3 \text{ K}$

$\Delta T_4 := T_{\text{in}_4} - T_{\text{ref}}$   $\Delta T_4 = 725 \text{ K}$

$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{in}_4} + c_4 \cdot (T_{\text{in}_4})^2 + d_4 \cdot (T_{\text{in}_4})^3 \right]$   $C_{p4} = -8.437 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{quicklime}} := m'_4 \cdot \left[ C_{p4} \cdot \Delta T_4 + H_{f_4} \right]$   $Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_5} = 1.023 \times 10^3 \text{ K}$

$\Delta T_5 := T_{\text{in}_5} - T_{\text{ref}}$   $\Delta T_5 = 725 \text{ K}$

$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{in}_5} + c_5 \cdot (T_{\text{in}_5})^2 + d_5 \cdot (T_{\text{in}_5})^3 \right]$   $C_{p5} = 1.3 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{carbondioxide}} := m'_5 \cdot \left[ C_{p5} \cdot \Delta T_5 + H_{f_5} \right]$   $Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{\text{in}_6} = 1.023 \times 10^3 \text{ K}$

$\Delta T_6 := T_{\text{in}_6} - T_{\text{ref}}$   $\Delta T_6 = 875 \text{ K}$

$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{in}_6} + c_5 \cdot (T_{\text{in}_6})^2 + d_6 \cdot (T_{\text{in}_6})^3 \right]$   $C_{p6} = 2.901 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{Natural.Gas}} := m'_6 \cdot \left[ C_{p6} \cdot \Delta T_6 + H_{f_6} \right]$   $Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$



### Total energy Input :

$$Q_{in} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{in} = -1.784 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

### ENERGY OUTPUT AROUND THE FLUIDIZED BED DECARBONIZER

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 54.84 \\ 0.00 \\ 67.85 \\ 10037.78 \\ 0.000 \\ 0.000 \end{pmatrix} \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{bmatrix} 800 \\ 800 \\ 800 \\ 800 \\ 800 \\ 800 \end{bmatrix} + 273.15 \cdot \text{K} \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 1.073 \times 10^3 \text{K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \quad \Delta T_1 = 775 \text{K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \quad C_{p1} = -1.481 \times 10^{10} \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot \left[ C_{p1} \cdot \Delta T_1 + H_{f1} \right] \quad Q_{\text{limestone}} = -6.294 \times 10^{14} \frac{\text{kJ}}{\text{hr}}$$

#### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 1.073 \times 10^3 \text{K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}} \quad \Delta T_2 = 775 \text{K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right] \quad C_{p2} = 33.711 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot \left[ C_{p2} \cdot \Delta T_2 + H_{f2} \right] \quad Q_{\text{water.}} = 0 \frac{\text{kJ}}{\text{hr}}$$

#### Energy of impurities(SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 1.073 \times 10^3 \text{K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}} \quad \Delta T_3 = 775 \text{K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right] \quad C_{p3} = 0.733 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot \left[ C_{p3} \cdot \Delta T_3 + H_{f3} \right]$$

$$Q_{\text{impure}} = -9.238 \times 10^5 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_4} = 1.073 \times 10^3 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}}$$

$$\Delta T_4 = 775 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right]$$

$$C_{p4} = -9.282 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot \left[ C_{p4} \cdot \Delta T_4 + H_{f4} \right]$$

$$Q_{\text{quicklime}} = -7.221 \times 10^{16} \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_5} = 1.073 \times 10^3 \text{ K}$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}}$$

$$\Delta T_5 = 775 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right]$$

$$C_{p5} = 1.307 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot \left[ C_{p5} \cdot \Delta T_5 + H_{f5} \right]$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_6} = 1.073 \times 10^3 \text{ K}$

$$\Delta T_6 := T_{\text{out}_6} - T_{\text{ref}}$$

$$\Delta T_6 = 775 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{out}_6} + c_5 \cdot (T_{\text{out}_6})^2 + d_6 \cdot (T_{\text{out}_6})^3 \right]$$

$$C_{p6} = 2.995 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot \left[ C_{p6} \cdot \Delta T_6 + H_{f6} \right]$$

$$Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -7.284 \times 10^{16} \frac{\text{kJ}}{\text{hr}}$$

### HEAT LOAD ON THE FLUIDIZED BED REACTOR:

$$Q_{\text{Fluidized.bed}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Fluidized.bed}} = -1.056 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

#### 4.1.8 ENERGY BALANCES AROUND THE CYCLONE

The energy balances cyclone will be calculated using

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

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 AROUND THE CYCLONE

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 310.77 \\ 0.00 \\ 271.38 \\ 0.000 \\ 7877.37 \\ 1524.61 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{in} := \begin{bmatrix} 800 \\ 800 \\ 800 \\ 800 \\ 800 \\ 800 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_1} = 1.073 \times 10^3 \text{ K}$

$$\Delta T_1 := T_{in_1} - T_{ref} \quad \Delta T_1 = 775 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{in_1} + c_1 \cdot (T_{in_1})^2 + d_1 \cdot (T_{in_1})^3 \right] \quad C_{p1} = -1.481 \times 10^{10} \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -3.567 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

#### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_2} = 1.073 \times 10^3 \text{ K}$

$$\Delta T_2 := T_{in_2} - T_{ref} \quad \Delta T_2 = 775 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{in_2} + c_2 \cdot (T_{in_2})^2 + d_2 \cdot (T_{in_2})^3 \right] \quad C_{p2} = 33.711 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water.}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Inlet temperature:  $T_{in_3} = 1.073 \times 10^3 K$

$$\Delta T_3 := T_{in_3} - T_{ref} \qquad \Delta T_3 = 775 K$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{in_3} + c_3 \cdot (T_{in_3})^2 + d_3 \cdot (T_{in_3})^3 \right] \qquad C_{p3} = 0.733 \frac{kJ}{kg \cdot K}$$

$$Q_{impure} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \qquad Q_{impure} = 1.541 \times 10^5 \frac{kJ}{hr}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Inlet temperature:  $T_{in_4} = 1.073 \times 10^3 K$

$$\Delta T_4 := T_{in_4} - T_{ref} \qquad \Delta T_4 = 775 K$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{in_4} + c_4 \cdot (T_{in_4})^2 + d_4 \cdot (T_{in_4})^3 \right] \qquad C_{p4} = -9.282 \times 10^9 \frac{kJ}{kg \cdot K}$$

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

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Inlet temperature:  $T_{in_5} = 1.073 \times 10^3 K$

$$\Delta T_5 := T_{in_5} - T_{ref} \qquad \Delta T_5 = 775 K$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{in_5} + c_5 \cdot (T_{in_5})^2 + d_5 \cdot (T_{in_5})^3 \right] \qquad C_{p5} = 1.307 \frac{kJ}{kg \cdot K}$$

$$Q_{carbondioxide} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \qquad Q_{carbondioxide} = 7.978 \times 10^6 \frac{kJ}{hr}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot K$

Inlet temperature:  $T_{in_6} = 1.073 \times 10^3 K$

$$\Delta T_6 := T_{in_6} - T_{ref} \qquad \Delta T_6 = 775 K$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{in_6} + c_5 \cdot (T_{in_6})^2 + d_6 \cdot (T_{in_6})^3 \right] \qquad C_{p6} = 2.995 \frac{kJ}{kg \cdot K}$$

$$Q_{Natural.Gas} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \qquad Q_{Natural.Gas} = 3.539 \times 10^6 \frac{kJ}{hr}$$

### Total energy Input :

$$Q_{in} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{in} = -3.567 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

### ENERGY OUTPUT AROUND THE CYCLONE

Given the mass and temperatures of the outlet as

$$m' := \begin{pmatrix} 77.69 \\ 0.00 \\ 67.85 \\ 0.000 \\ 7483.50 \\ 1448.38 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{\text{out}} := \begin{bmatrix} 250 \\ 250 \\ 250 \\ 250 \\ 250 \\ 250 \end{bmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_1} = 523.15 \text{ K}$

$$\Delta T_1 := T_{\text{out}_1} - T_{\text{ref}} \quad \Delta T_1 = 225 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{\text{out}_1} + c_1 \cdot (T_{\text{out}_1})^2 + d_1 \cdot (T_{\text{out}_1})^3 \right] \quad C_{p1} = -3.519 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -6.152 \times 10^{13} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_2} = 523.15 \text{ K}$

$$\Delta T_2 := T_{\text{out}_2} - T_{\text{ref}} \quad \Delta T_2 = 225 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{\text{out}_2} + c_2 \cdot (T_{\text{out}_2})^2 + d_2 \cdot (T_{\text{out}_2})^3 \right] \quad C_{p2} = 4.831 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water.}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_3} = 523.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}} \quad \Delta T_3 = 225 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right] \quad C_{p3} = 0.487 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 7.435 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_4} = 523.15 \text{ K}$$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}} \quad \Delta T_4 = 225 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right] \quad C_{p4} = -2.206 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{\text{quicklime}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_5} = 523.15 \text{ K}$$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}} \quad \Delta T_5 = 225 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right] \quad C_{p5} = 1.168 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 1.967 \times 10^6 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

$$\text{Reference temperature: } T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$$

$$\text{Outlet temperature: } T_{\text{out}_6} = 523.15 \text{ K}$$

$$\Delta T_6 := T_{\text{out}_6} - T_{\text{ref}} \quad \Delta T_6 = 225 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{out}_6} + c_6 \cdot (T_{\text{out}_6})^2 + d_6 \cdot (T_{\text{out}_6})^3 \right] \quad C_{p6} = 2.599 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6$$

$$Q_{\text{Natural.Gas}} = 8.469 \times 10^5 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -6.152 \times 10^{13} \frac{\text{kJ}}{\text{hr}}$$

### HEAT LOAD ON THE CYCLONE:

$$Q_{\text{Cyclone}} := Q_{\text{in}} - Q_{\text{out}}$$

$$Q_{\text{Cyclone}} = -3.505 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

#### 4.1.8 ENERGY BALANCES AROUND THE COOLER

The energy balances around the cooler will be calculated using

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

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 AROUND THE COOLER

Given the mass and temperatures of the input as

$$m' := \begin{pmatrix} 54.84 \\ 0.00 \\ 67.85 \\ 10037.78 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{in} := \begin{pmatrix} 250 \\ 250 \\ 250 \\ 250 \\ 250 \\ 250 \end{pmatrix} + 273.15 \cdot \text{K} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

#### Energy of calcium carbonate (CaCO<sub>3</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_1} = 523.15 \text{ K}$

$\Delta T_1 := T_{in_1} - T_{ref} \quad \Delta T_1 = 225 \text{ K}$

$C_{p1} := \left[ a_1 + b_1 \cdot T_{in_1} + c_1 \cdot (T_{in_1})^2 + d_1 \cdot (T_{in_1})^3 \right] \quad C_{p1} = -3.519 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -4.342 \times 10^{13} \frac{\text{kJ}}{\text{hr}}$

#### Energy of moisture (H<sub>2</sub>O) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_2} = 523.15 \text{ K}$

$\Delta T_2 := T_{in_2} - T_{ref} \quad \Delta T_2 = 225 \text{ K}$

$C_{p2} := \left[ a_2 + b_2 \cdot T_{in_2} + c_2 \cdot (T_{in_2})^2 + d_2 \cdot (T_{in_2})^3 \right] \quad C_{p2} = 4.831 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$

$Q_{\text{water}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water}} = 0 \frac{\text{kJ}}{\text{hr}}$

#### Energy of impurities (SiO<sub>2</sub>) at the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_3} = 523.15 \text{ K}$

$$\Delta T_3 := T_{in_3} - T_{ref} \quad \Delta T_3 = 225 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{in_3} + c_3 \cdot (T_{in_3})^2 + d_3 \cdot (T_{in_3})^3 \right] \quad C_{p3} = 0.487 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{impure} := m'_3 \cdot C_{p3} \cdot \Delta T_3 \quad Q_{impure} = 7.435 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_4} = 523.15 \text{ K}$

$$\Delta T_4 := T_{in_4} - T_{ref} \quad \Delta T_4 = 225 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{in_4} + c_4 \cdot (T_{in_4})^2 + d_4 \cdot (T_{in_4})^3 \right] \quad C_{p4} = -2.206 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{quicklime} := m'_4 \cdot C_{p4} \cdot \Delta T_4 \quad Q_{quicklime} = -4.982 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_5} = 523.15 \text{ K}$

$$\Delta T_5 := T_{in_5} - T_{ref} \quad \Delta T_5 = 225 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{in_5} + c_5 \cdot (T_{in_5})^2 + d_5 \cdot (T_{in_5})^3 \right] \quad C_{p5} = 1.168 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{carbondioxide} := m'_5 \cdot C_{p5} \cdot \Delta T_5 \quad Q_{carbondioxide} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the inlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Inlet temperature:  $T_{in_6} = 523.15 \text{ K}$

$$\Delta T_6 := T_{in_6} - T_{ref} \quad \Delta T_6 = 225 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{in_6} + c_6 \cdot (T_{in_6})^2 + d_6 \cdot (T_{in_6})^3 \right] \quad C_{p6} = 2.599 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{Natural.Gas} := m'_6 \cdot C_{p6} \cdot \Delta T_6 \quad Q_{Natural.Gas} = 0 \frac{\text{kJ}}{\text{hr}}$$



## Total energy Input :

$$Q_{in} := Q_{\text{limestone}} + Q_{\text{water.}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{in} = -1.206 \times 10^{17} \frac{\text{kJ}}{\text{day}}$$

## ENERGY OUTPUT AROUND THE COOLER

Given the mass and temperatures of the cooler outlet as

$$m' := \begin{pmatrix} 54.84 \\ 0.00 \\ 67.85 \\ 10037.78 \\ 0.000 \\ 0.000 \end{pmatrix} \frac{\text{kg}}{\text{hr}} \quad \text{and} \quad T_{out} := \begin{bmatrix} 150 \\ 150 \\ 150 \\ 150 \\ 150 \\ 150 \end{bmatrix} + 273.15 \cdot \text{K} \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

### Energy of calcium carbonate (CaCO<sub>3</sub>) in the outlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_1} = 423.15 \text{ K}$

$$\Delta T_1 := T_{out_1} - T_{ref} \quad \Delta T_1 = 125 \text{ K}$$

$$C_{p1} := \left[ a_1 + b_1 \cdot T_{out_1} + c_1 \cdot (T_{out_1})^2 + d_1 \cdot (T_{out_1})^3 \right] \quad C_{p1} = -2.302 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{limestone}} := m'_1 \cdot C_{p1} \cdot \Delta T_1 \quad Q_{\text{limestone}} = -1.578 \times 10^{13} \frac{\text{kJ}}{\text{hr}}$$

### Energy of moisture (H<sub>2</sub>O) in the outlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_2} = 423.15 \text{ K}$

$$\Delta T_2 := T_{out_2} - T_{ref} \quad \Delta T_2 = 125 \text{ K}$$

$$C_{p2} := \left[ a_2 + b_2 \cdot T_{out_2} + c_2 \cdot (T_{out_2})^2 + d_2 \cdot (T_{out_2})^3 \right] \quad C_{p2} = 4.325 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{water.}} := m'_2 \cdot C_{p2} \cdot \Delta T_2 \quad Q_{\text{water.}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of impurities(SiO<sub>2</sub>) at the outlet

Reference temperature:  $T_{ref} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{out_3} = 423.15 \text{ K}$

$$\Delta T_3 := T_{\text{out}_3} - T_{\text{ref}}$$

$$\Delta T_3 = 125 \text{ K}$$

$$C_{p3} := \left[ a_3 + b_3 \cdot T_{\text{out}_3} + c_3 \cdot (T_{\text{out}_3})^2 + d_3 \cdot (T_{\text{out}_3})^3 \right]$$

$$C_{p3} = 0.442 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{impure}} := m'_3 \cdot C_{p3} \cdot \Delta T_3$$

$$Q_{\text{impure}} = 3.752 \times 10^3 \frac{\text{kJ}}{\text{hr}}$$

### Energy of calcium oxide (CaO) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_4} = 423.15 \text{ K}$

$$\Delta T_4 := T_{\text{out}_4} - T_{\text{ref}}$$

$$\Delta T_4 = 125 \text{ K}$$

$$C_{p4} := \left[ a_4 + b_4 \cdot T_{\text{out}_4} + c_4 \cdot (T_{\text{out}_4})^2 + d_4 \cdot (T_{\text{out}_4})^3 \right]$$

$$C_{p4} = -1.443 \times 10^9 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{quicklime}} := m'_4 \cdot C_{p4} \cdot \Delta T_4$$

$$Q_{\text{quicklime}} = -1.811 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

### Energy of carbon dioxide (CO<sub>2</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_5} = 423.15 \text{ K}$

$$\Delta T_5 := T_{\text{out}_5} - T_{\text{ref}}$$

$$\Delta T_5 = 125 \text{ K}$$

$$C_{p5} := \left[ a_5 + b_5 \cdot T_{\text{out}_5} + c_5 \cdot (T_{\text{out}_5})^2 + d_5 \cdot (T_{\text{out}_5})^3 \right]$$

$$C_{p5} = 1.123 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{carbondioxide}} := m'_5 \cdot C_{p5} \cdot \Delta T_5$$

$$Q_{\text{carbondioxide}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Energy of Natural Gas (CH<sub>4</sub>) in the outlet

Reference temperature:  $T_{\text{ref}} := (25 + 273.15) \cdot \text{K}$

Outlet temperature:  $T_{\text{out}_6} = 423.15 \text{ K}$

$$\Delta T_6 := T_{\text{out}_6} - T_{\text{ref}}$$

$$\Delta T_6 = 125 \text{ K}$$

$$C_{p6} := \left[ a_6 + b_6 \cdot T_{\text{out}_6} + c_6 \cdot (T_{\text{out}_6})^2 + d_6 \cdot (T_{\text{out}_6})^3 \right]$$

$$C_{p6} = 2.394 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$Q_{\text{Natural.Gas}} := m'_6 \cdot C_{p6} \cdot \Delta T_6$$

$$Q_{\text{Natural.Gas}} = 0 \frac{\text{kJ}}{\text{hr}}$$

### Total energy Output :

$$Q_{\text{out}} := Q_{\text{limestone}} + Q_{\text{water}} + Q_{\text{impure}} + Q_{\text{quicklime}} + Q_{\text{carbondioxide}} + Q_{\text{Natural.Gas}}$$

$$Q_{\text{out}} = -1.827 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

**HEAT LOAD ON THE COOLER:**  $Q_{\text{cooler}} := Q_{\text{in}} - Q_{\text{out}}$

$$Q_{\text{cooler}} = -3.199 \times 10^{15} \frac{\text{kJ}}{\text{hr}}$$

### Summary of the Energy Balance of the Process

Equipment	Heat Load (kJ/hr)
Bin	7.91E+13
Pre Crusher	2.41E+14
Screeners 1	-9.42E+13
Crusher	1.99E+14
Screeners 2	9.57E+13
Dryer	1.78E+17
Fluidized Bed Reactor	-1.06E+17
Cyclone	-3.51E+15
Cooler	-3.20E+15
<b>Total Heat on the Process</b>	<b>6.61E+16</b>

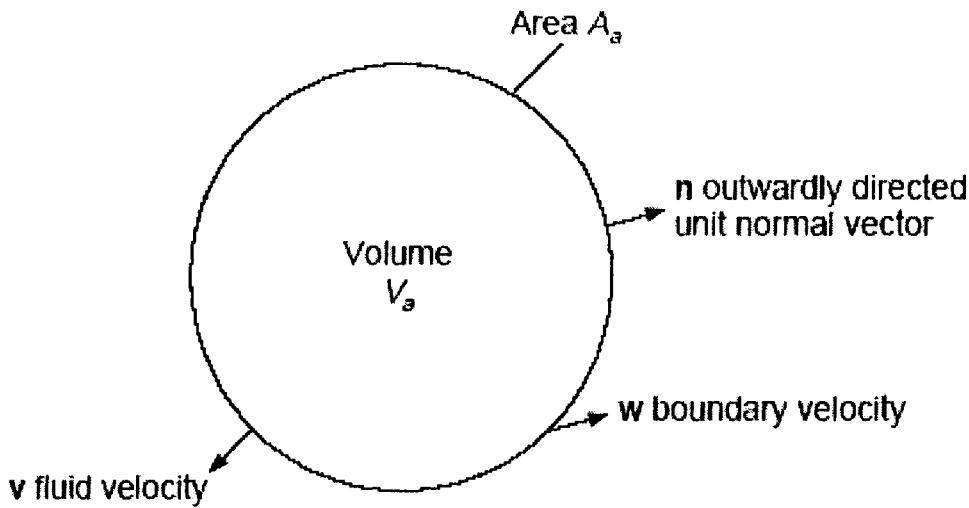
## 4.2 MOMENTUM BALANCE

### 4.2.1 Theory of Momentum Balance

Since momentum is a vector quantity, the momentum balance is a vector equation. Where gravity is the only body force acting on the fluid, the linear momentum principle, applied to the arbitrary control volume of Fig. 4.1, results in the following expression

$$\frac{d}{dt} \int \rho v dV + \int \rho v(v - w) \cdot n dA = \int \rho g dV + \int t_n dA$$

(Perry, 1997)



**Fig 4.2 arbitrary control volume for application of conservation Equations**

Here  $g$  is the gravity vector and  $t_n$  is the force per unit area exerted by the surroundings on the fluid in the control volume. The integrand of the area integral on the left-hand side of Equation. is nonzero only on the entrance and exit portions of the control volume boundary. For the special case of steady flow at a mass flow rate  $\dot{m}$  through a control volume fixed in space with one inlet and one outlet, with the inlet and outlet velocity vectors perpendicular to planar inlet and outlet surfaces, giving average velocity vectors  $V_1$  and  $V_2$ , the momentum equation becomes

$$m(\beta_2 \cdot V_2 - \beta_1 \cdot V_1) = -\rho_1 \cdot A_1 - \rho_2 \cdot A_2 + F + Mg$$

Where  $M$  is the total mass of fluid in the control volume. The factor  $\beta$  arises from the averaging of the velocity across the area of the inlet or outlet surface. It is the ratio of the area average of the square of velocity magnitude to the square of the area average velocity magnitude. For a uniform velocity,  $\beta = 1$ . For turbulent flow,  $\beta$  is nearly unity, while for laminar pipe flow with a parabolic velocity profile,  $\beta = 4/3$ . The vectors  $A_1$  and  $A_2$  have magnitude equal to the areas of the inlet and outlet surfaces, respectively, and are outwardly directed normal to the surfaces. The vector  $F$  is the force exerted on the fluid by the nonflow boundaries of the control volume.

(Perry, 1997)

For this plant, the momentum balance will be carried out for the fluidized bed reactor, since it is the only

equipment in which the limestone particles moved in countercurrent flow with the natural gas.

### **Theory of Particulate Fluidization**

In *particulate fluidization*, as the fluid velocity is increased the bed continues to expand and remains homogeneous for a time. The particles move farther apart and their motion becomes more rapid. The average bed density at a given velocity is the same in all regions of the bed. An example is catalytic cracking catalysts fluidized by gases. This type of fluidization is very desirable in promoting intimate contact between the gas and solids. Liquids often give particulate fluidization.

### **Minimum velocity and porosity for particulate fluidization**

When a fluid flows upward through a packed bed of particles at low velocities, the particles remain stationary. As the fluid velocity is increased, the pressure drop increases according to the Ergun equation. Upon further increases in velocity, conditions finally occur where the force of the pressure drop times the cross-sectional area equals the gravitational force on the mass of particles. Then the particles begin to move, and this is the onset of fluidization or minimum fluidization. The fluid velocity at which fluidization begins is the minimum fluidization velocity  $v'_{mf}$  in m/s based on the empty cross section of the tower (superficial velocity).

The porosity of the bed when true fluidization occurs is the minimum porosity for fluidization,  $\epsilon_{mf}$ . The bed expands to this voidage or porosity before particle motion appears. This minimum voidage can be determined experimentally by subjecting the bed to a rising gas stream and measuring the height of the bed  $L_{mf}$  in m. Generally, it appears best to use gas as the fluid rather than a liquid, since liquids give somewhat higher values of  $\epsilon_{mf}$ .

As stated earlier, the pressure drop increases as the gas velocity is increased until the onset of minimum fluidization. Then, as the velocity is further increased, the pressure drop decreases very slightly, and then it remains practically unchanged as the bed continues to expand or increase in porosity with increases in velocity. The bed resembles a boiling liquid. As the bed expands with increase in velocity, it continues to retain its top horizontal surface. Eventually, as the velocity is increased much further, entrainment of particles from the actual fluidized bed becomes appreciable.

The relation between bed height  $L$  and porosity  $\epsilon$  is as follows for a bed having a uniform cross-sectional area  $A$ . Since the volume  $LA(1 - \epsilon)$  is equal to the total volume of solids if they existed as one piece,

$$L_1 A(1 - \epsilon_1) = L_2 A(1 - \epsilon_2) \quad \dots\dots\dots(1)$$

$$\frac{L_1}{L_2} = \frac{1 - \epsilon_2}{1 - \epsilon_1} \quad \dots\dots\dots(2)$$

Where  $L_1$  is height of bed with porosity  $\epsilon_1$  and  $L_2$  is height with porosity  $\epsilon_2$ .

**Pressure drop and minimum fluidizing velocity**

As a first approximation, the pressure drop at the start of fluidization can be determined as follows. The force obtained from the pressure drop times the cross-sectional area must equal the gravitational force exerted by the mass of the particles minus the buoyant force of the displaced fluid:

$$\Delta p A = L_{mf} \cdot A(1 - \epsilon_{mf})(\rho_p - \rho)g \quad \dots\dots\dots(3)$$

Hence,

$$\frac{\Delta p}{L_{mf}} = (1 - \epsilon_{mf})(\rho_p - \rho)g \quad \text{(S I) .....(4a)}$$

$$\frac{\Delta p}{L_{mf}} = (1 - \epsilon_{mf})(\rho_p - \rho) \frac{g}{g_c} \quad \text{(English) .....(4b)}$$

Often we have irregular-shaped particles in the bed, and it is more convenient to use the particle size and shape factor in the equations. First we substitute for the effective mean diameter  $D_p$  the term  $\phi_s D_p$ , where  $D_p$  now represents the particle size of a sphere having the same volume as the particle and  $\phi_s$  the shape factor. Often, the value of  $D_p$  is approximated by using the nominal size from a sieve analysis. Then Equation for pressure drop in a packed bed becomes

$$\frac{\Delta p}{L} = \frac{150 \mu}{\Phi_s^2 D_p} \frac{V'' (1 - \epsilon)^2}{\epsilon^3} + \frac{1.75 \rho (V'')^2}{\Phi_s D_p} \cdot \frac{1 - \epsilon}{\epsilon^3} \quad \text{.....(5)}$$

where  $\Delta L = L$ , bed length in m.

Equation (5) can now be used by a small extrapolation for packed beds to calculate the minimum fluid velocity  $V'_{mf}$  at which fluidization begins by substituting  $V'_{mf}$  for  $V'$ ,  $\epsilon_{mf}$  for  $\epsilon$ , and  $L_{mf}$  for  $L$ , and combining the result with Eq. (4) to give

$$\frac{1.75 \rho (V'_{mf})^2 \rho^2}{\Phi_s \epsilon_{mf}^3 D_p} + \frac{150 (1 - \epsilon_{mf}) D_p V'_{mf} \rho}{\Phi_s^2 \epsilon_{mf}^3 \mu} - \frac{D_p^3 \rho (\rho_p - \rho) \cdot g}{\mu^2} = 0 \quad \text{.....(6)}$$

Defining a Reynolds number as

$$N_{Re,mf} = \frac{D_p \cdot V'_{mf} \cdot \rho}{\mu} \quad \text{.....(7)}$$

Eq. (6) becomes

$$\frac{1.75 \rho (N_{Re,mf})^2}{\Phi_s \epsilon_{mf}^3} + \frac{150 (1 - \epsilon_{mf}) (N_{Re,mf})}{\Phi_s^2 \epsilon_{mf}^3} - \frac{D_p^3 \rho (\rho_p - \rho) \cdot g}{\mu^2} \quad \text{.....(8)}$$

When  $N_{Re,mf} < 20$  (small particles), the first term of Eq. (8) can be dropped, and when

$N_{Re,mf} > 1000$  (large particles), the second term drops out.

If the terms  $\epsilon_{mf}$  and/or  $\phi_s$  are not known, Wen and Yu (Perry, 1997) found for a variety of systems that

$$\Phi_s \epsilon_{mf}^3 = \frac{1}{14}, \quad \frac{1 - \epsilon_{mf}}{\Phi_s^2 \epsilon_{mf}^3} = 11 \quad \dots\dots\dots(9)$$

Substituting into Eq. (8), the following simplified equation is obtained

$$N_{Re,mf} = \left[ (33.7)^2 + 0.0408 \cdot \frac{D_p^3 \rho (\rho_p - \rho) \cdot g}{\mu^2} \right]^{0.5} - 33.7 \quad \dots\dots\dots(10)$$

This equation holds for a Reynolds-number range of 0.001 to 4000, with an average deviation of  $\pm 25\%$ .

**Hence in determining the minimum velocity of the particle in the fluidized bed reactor, the**

**following conditions are Assumed:**

**Particle Size of Limestone :**  $D_p := 3.2 \cdot 10^{-3} m$

**Density of Particle is the average density  $\rho_{av}$  of Limestone Composition obtained as shown below:**

Denoting the mass of the components by  $m'$ , the density by  $\rho$ , the molecular weight by molwt; ar amount in moles  $n$ .

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

$$\rho := \begin{pmatrix} 2930 \\ 1000 \\ 2250 \\ 2620 \\ 1530 \end{pmatrix} \cdot \frac{kg}{m^3} \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ Impurities \\ CaO \\ CO_2 \end{pmatrix}$$

$$M_w := \begin{pmatrix} 100.090 \\ 18.016 \\ 60.000 \\ 56.080 \\ 44.010 \end{pmatrix} \cdot \frac{kg}{kmol} \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ Impurities \\ CaO \\ CO_2 \end{pmatrix}$$

(Himmeblau, 1996)

**Masses of the limestone component at Fluidized bed Inlet:**

$$m' := \begin{pmatrix} 18280.76 \\ 0.00 \\ 339.23 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{kg}{hr} \quad \begin{pmatrix} CaCO_3 \\ H_2O \\ Impurities \\ CaO \\ CO_2 \end{pmatrix}$$

$$\begin{pmatrix} 18280.76 \\ 0.00 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix}$$



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

$$n := \frac{\overset{\rightarrow}{m'}}{M_w} \quad n = \begin{pmatrix} 182.643 \\ 0 \\ 5.654 \\ 0 \\ 0 \end{pmatrix} \frac{\text{kmol}}{\text{hr}}$$

The average density of the components is calculated as;

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

$$\rho_{av} = 2909.582 \frac{\text{kg}}{\text{m}^3} \quad \rho_p := \rho_{av}$$

**Density of Particle:**  $\rho_p = 2909.582 \text{ kg m}^{-3}$

**The Fluidizing gas is Natural Gas (CH<sub>4</sub>) with the following Properties :**

Hence,

**Density :**  $\rho := 544 \frac{\text{kg}}{\text{m}^3}$  , **Viscosity:**  $\mu$

The vapour viscosity will be predicted using the Stiel and Thodos corellation :

$$\mu_{\text{gas}} = 4.60 \cdot 10^{-4} \cdot \frac{N \cdot M_g^2 \cdot P_c^3}{T_c^6}$$

where,

$$N = 0.0003400 T_r^{0.94} \quad \text{for } T_r < 1.5$$

$$N = 0.0001778 (4.58 \cdot T_r - 1.67)^{0.625} \quad \text{for } T_r > 1.5$$

$$T_c := 190.6\text{K} \quad P_c := 45.4\text{atm} \quad \text{for Natural Gas}$$

$$P_c = 4600155 \text{ Pa}$$

Hence from the Energy Balance the Temperature of the Natural Gas :

$$T_{\text{gas}} := (900 + 273.15)\text{K} \quad M_g := 16.010 \frac{\text{kg}}{\text{kgmole}}$$

The Vapour pressure of the gas is obtained from the Antoine Equation:

$$\ln(P_{\text{gas}}) = A' - \frac{B'}{T_{\text{gas}} + C'}$$

$$A' := 15.2243 \quad B' := 897.84\text{K} \quad C' := -7.16\text{K}$$

$$P_{\text{gas}} := e^{\left(\frac{A' - B'}{T_{\text{gas}} + C'}\right)} \quad P_{\text{gas}} = 1894141.4693 \text{ mmHg} \quad P_{\text{gas}} = 2492.291 \text{ atm}$$

Hence the  $P_r$  and  $T_r$  are computed thus :

$$P_r := \frac{P_{\text{gas}}}{P_c} \quad P_r = 0.4118 \text{ m s}^{-2} \text{ kg}^{-1} \quad T_r := \frac{T_{\text{gas}}}{T_c} \quad T_r = 6.155$$

$$N := 0.0001778 (4.58 \cdot T_r - 1.67)^{0.625} \quad N = 0.0014$$

$$\mu_{\text{gas}} := 4.60 \cdot 10^{-4} \cdot \frac{N \cdot M \cdot g^{\frac{1}{2}} \cdot P_c^{\frac{2}{3}}}{T_c^{\frac{1}{6}}} \quad \mu_{\text{gas}} = 0.0293 \text{ kg}^1 \text{ m}^0 \text{ s}^{-1} \text{ K}^0$$

$$g := 9.81 \frac{\text{m}}{\text{s}^2} \quad \mu := 0.0293 \frac{\text{kg}}{\text{m} \cdot \text{s}}$$

$$N_{\text{Re.mf}} := \left[ \left[ (33.7)^2 + 0.0408 \cdot \frac{D_p^3 \rho \cdot (\rho_p - \rho) \cdot g}{\mu^2} \right]^{0.5} - 33.7 \right]$$

$$N_{\text{Re.mf}} = 0.2904$$

From Equation (7): 
$$V'_{\text{mf}} = \frac{N_{\text{Re.mf}} \cdot \mu}{D_p \cdot \rho}$$

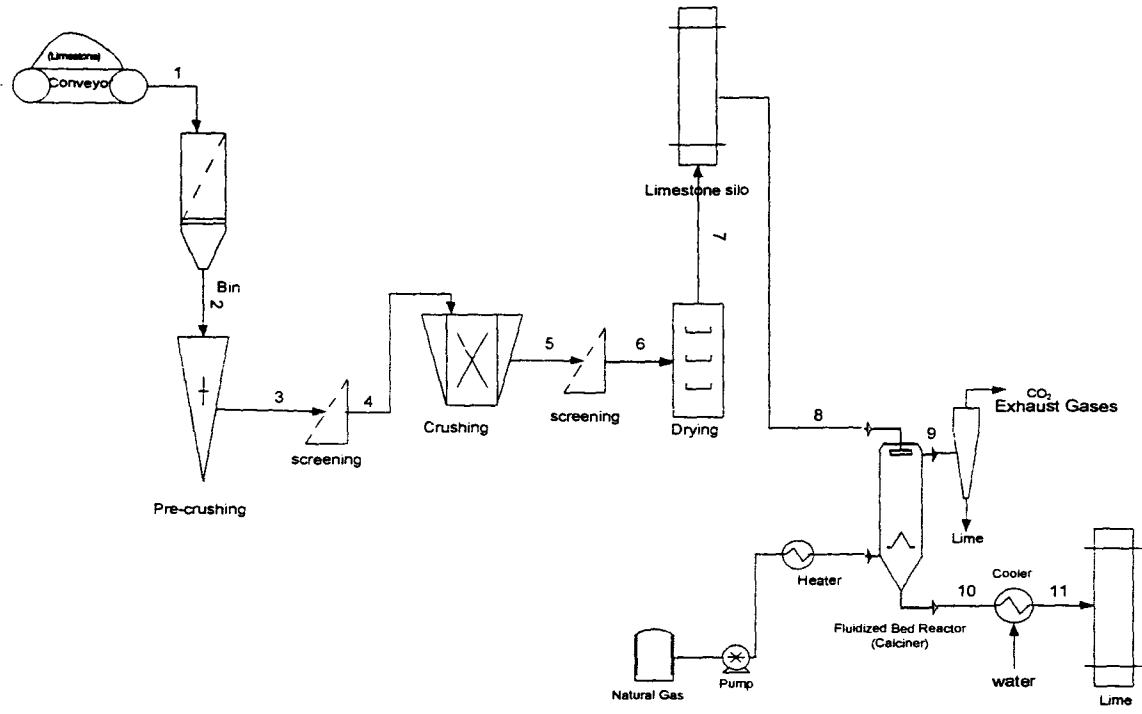
$$V'_{\text{mf}} := \frac{N_{\text{Re.mf}} \cdot \mu}{D_p \cdot \rho}$$

**Hence the minimum fluidization velocity in the Fluidized Bed Reactor:**

$$V'_{\text{mf}} = 0.0049 \text{ m s}^{-1}$$

CHAPTER FIVE

5.0 FLOWSHEETING



Flowsheet for the Production of Quicklime from Limestone

Flows (kg/hr)

Line No	1	2	3	4	5	6	7	8	9	10	11
Component	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)	mass (kg/hr)
CaCO <sub>3</sub>	19323.92	19323.92	19227.30	19035.03	18749.50	18280.76	18280.76	18280.76	310.77	54.84	54.84
H <sub>2</sub> O	239.06	239.06	237.86	235.48	231.95	226.15	0.00	0.00	0.00	0.00	0.00
Clavey impurities	358.59	358.59	356.80	353.23	347.93	339.23	339.23	339.23	271.38	67.85	67.85
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10037.78	10037.78
CO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7877.37	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1524.61	0.00	0.00
Total	19921.57	19921.57	19821.96	19623.74	19329.38	18846.15	18619.99	18619.99	9984.13	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  $\rho$ , the molecular weight by  $M_w$ ; and amount in moles  $n$ .

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

$$m' := \begin{pmatrix} 19323.92 \\ 239.06 \\ 358.59 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \rho := \begin{pmatrix} 2930 \\ 1000 \\ 2250 \\ 2620 \\ 1530.0 \\ 554.0 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3} \quad M_w := \begin{pmatrix} 100.090 \\ 18.016 \\ 60.000 \\ 56.080 \\ 44.010 \\ 16.040 \end{pmatrix} \cdot \frac{\text{kg}}{\text{kmol}} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

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

$$n := \frac{m'}{M_w} \rightarrow n = \begin{pmatrix} 193.065 \\ 13.269 \\ 5.976 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot \frac{\text{kmol}}{\text{hr}} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

The average density of the components is calculated as;

$$\rho_{av} := \left( \frac{n_1}{\sum n} \cdot \rho_1 + \frac{n_2}{\sum n} \cdot \rho_2 + \frac{n_3}{\sum n} \cdot \rho_3 + \frac{n_4}{\sum n} \cdot \rho_4 + \frac{n_5}{\sum n} \cdot \rho_5 + \frac{n_6}{\sum n} \cdot \rho_6 \right)$$

$$\rho_{av} = 2790.234 \frac{\text{kg}}{\text{m}^3}$$

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

$$V_{bin} := \frac{m_{bin}}{\rho_{av}} \quad V_{bin} = 7.14 \frac{\text{m}^3}{\text{hr}}$$

The bin is cylindrical with conical bottom, hence

$V_{Bin}$  = "volume of cylindrical top + volume of conical bottom"

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

Total volume of the bin is then

$$V_{\text{bin}} = V_{\text{top}} + V_{\text{bottom}} \quad V_{\text{bin}} = \pi \cdot R^2 \cdot H + \frac{1}{3} \pi \cdot R^2 \cdot h \quad R = \frac{D}{2}$$

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

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  $h = k \cdot r \cdot D$

After substitution,

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

becomes

$$V_{\text{bin}} = \pi \cdot \left(\frac{D_{\text{bin}}}{2}\right)^2 \cdot r \cdot D_{\text{bin}} + \frac{1}{3} \pi \cdot \left(\frac{D_{\text{bin}}}{2}\right)^2 \cdot k \cdot r \cdot D$$

$$V_{\text{bin}} = \frac{\pi \cdot r}{4} \cdot (D_{\text{bin}})^3 + \frac{\pi \cdot k \cdot r}{12} \cdot (D_{\text{bin}})^3$$

$$V_{\text{bin}} = (D_{\text{bin}})^3 \cdot \left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right) \quad (D_{\text{bin}})^3 = \frac{V_{\text{bin}}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)}$$

Making the diameter of the bin ( $D_{\text{bin}}$ ) the subject of the formular

$$D_{\text{bin}} = \left[ \frac{V_{\text{bin}}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)} \right]^{\frac{1}{3}} \quad V_{\text{bin}} := V_{\text{bin}} \cdot \text{hr}$$

$$D_{\text{bin}} := \left[ \frac{V_{\text{bin}}}{\left(\frac{\pi \cdot r}{4} + \frac{\pi \cdot k \cdot r}{12}\right)} \right]^{\frac{1}{3}} \quad D_{\text{bin}} = 1.616 \text{ m}$$

Based on the assumption that  $H = 2D$ ,

$$H_{\text{top}} := r \cdot D_{\text{bin}} \quad H_{\text{top}} = 3.232 \text{ m}$$

$$h_{\text{bottom}} := k \cdot H_{\text{top}} \quad h_{\text{bottom}} = 0.743 \text{ m}$$

Total height of the bin is therefore,

$$H_{\text{bin}} := H_{\text{top}} + h_{\text{bottom}} \quad H_{\text{bin}} = 3.976 \text{ m}$$

The area of the bin is thus calculated as the sum of the area of cylindrical and the frustrum part. That is,

$$A_{\text{bin}} := \left[ 2 \cdot \pi \cdot \left(\frac{D_{\text{bin}}}{2}\right) \cdot H_{\text{top}} + 2 \cdot \pi \cdot \left(\frac{D_{\text{bin}}}{2}\right)^2 \right] + \pi \cdot \frac{D_{\text{bin}}}{2} \cdot h_{\text{bottom}} \quad A_{\text{bin}} = 22.403 \text{ m}^2$$

## 6.1.2 DESIGN OF PRE-CRUSHER

**Type: Jaw crusher**

**Material of construction: Steel**

The crusher is used to reduce the size of the limestone with the aid of the crushing ability it poss

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 materials in the crusher to be:

$$M := \begin{pmatrix} 19323.92 \\ 239.06 \\ 358.59 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \rho := \begin{pmatrix} 2650 \\ 1000 \\ 2250 \\ 2620 \\ 1530 \\ 554.0 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

The average density of the materials in the crusher can be calculated as;

$$\rho_{\text{av}} := \frac{(M_1 \cdot \rho_1 + M_2 \cdot \rho_2 + M_3 \cdot \rho_3 + M_4 \cdot \rho_4 + M_5 \cdot \rho_5 + M_6 \cdot \rho_6)}{(\sum M)} \quad \rho_{\text{av}} = 2623 \frac{\text{kg}}{\text{m}^3}$$

The total mass of the materials in the pre-crusher is given as

$$\sum M = 1.992 \times 10^4 \frac{\text{kg}}{\text{hr}}$$

So, the volume is calculated to be

$$V_{\text{pre.crusher}} := \frac{\sum M}{\rho_{\text{av}}} \quad V_{\text{pre.crusher}} = 7.595 \frac{\text{m}^3}{\text{hr}}$$

The volume occupied by the rolls can be 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,

$$d := 1.33 \cdot \text{cm}$$

$$d = 0.013 \text{ m}$$

$$L := 1.15 \cdot \text{cm}$$

$$L = 0.011 \text{ m}$$

$$s' := 7 \cdot \frac{\text{cm}}{\text{min}}$$

$$s' = 1.167 \times 10^{-3} \frac{\text{m}}{\text{s}}$$

$$Q_{\text{pre.crusher}} := \frac{(d \cdot L \cdot s')}{2.96}$$

$$Q_{\text{pre.crusher}} = 2.17 \times 10^{-4} \frac{\text{m}^3}{\text{hr}}$$

The total volume of the pre-crusher is thus

$$Q_{\text{pre.crusher}} := Q_{\text{pre.crusher}}$$

$$V_{\text{Tpre.crusher}} := V_{\text{pre.crusher}} + Q_{\text{pre.crusher}}$$

$$V_{\text{Tpre.crusher}} = 7.595 \frac{\text{m}^3}{\text{hr}}$$

The volume of the pre-crusher is given as:

$$V = \pi \cdot r^2 \cdot h \quad \text{and, since}$$

$$r = \frac{d}{2}$$

$$V = \pi \cdot \left(\frac{d}{2}\right)^2 \cdot h$$

$$V = \pi \cdot \frac{d^2}{4} \cdot h$$

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  $k := 1.25$

$$V_{\text{Tpre.crusher}} := V_{\text{Tpre.crusher}} \cdot \text{hr}$$

$$d_{\text{pre.crusher}} := \left(\frac{4 \cdot V_{\text{Tpre.crusher}}}{k \cdot \pi}\right)^{\frac{1}{3}}$$

$$d_{\text{pre.crusher}} = 1.978 \text{ m}$$

From

$$h_{\text{pre.crusher}} := k \cdot d_{\text{pre.crusher}}$$

$$h_{\text{pre.crusher}} = 2.472 \text{ m}$$

The area of the pre-crusher is therefore,

$$A := 2\pi \cdot \frac{d_{\text{pre.crusher}}}{2} \cdot h_{\text{pre.crusher}} + 2\pi \cdot \left(\frac{d_{\text{pre.crusher}}}{2}\right)^2$$

$$A = 21.505 \text{ m}^2$$

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

$$L = 0.011 \text{ m}$$

$$K_r := 0.9$$

$$D := d_{\text{pre.crusher}}$$

$$E_2 := 9.5 \cdot W \quad (\text{Ernest, 1995})$$

So, the net power used by the roll is

$$E_{\text{roll}} := [(1.64 \cdot L - 1 \cdot \text{m}) \cdot K_r + 1 \text{m}] (1.64 \cdot D)^{2.5} \cdot E_2 \cdot \text{m}^{-3.5}$$

$$E_{\text{roll}} = 21.056 \text{ W}$$

### 6.1.3 DESIGN OF SCREENER 1

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 portions consisting of grains of more uniform size than those of 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 screen surface and retained on a subsequent surface is the intermediate material.

The screening surface may consist of woven-wire, silk, or plastic cloth, perforated or punched p grizzly bars, or wedge wire sections. (Perry, 1998)

#### Screen Efficiency

A sound method of evaluating screen performance is given by W. S. Tyler, Inc., Mentor, Ohio 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 screener 1 efficiency

In this project, the efficiency of the screen will be given as

$$E = \frac{R \cdot d}{b}$$

when R := 85% d := 8.05% b := 6.95%

Therefore, from

$$E := \frac{R \cdot d}{b} \quad E = 0.985$$

### Estimating Screen Capacity

Various methods of predicting screening capacity have been proposed, and each has its limitations. The throughflow method of Mathews uses the following equation:

$$A = \frac{0.4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s} \quad (\text{Perry, 1998})$$

where A = "screen area" C<sub>t</sub> = "throughflow rate" C<sub>u</sub> = "unit capacity"

$F_{oa}$  = "open-area factor"

$F_s$  = "slotted-area factor"

Given that,

$$m' := \begin{pmatrix} 19227.30 \\ 237.86 \\ 356.80 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad C_t := \sum m'$$

$$C_t = 1.982 \times 10^4 \frac{\text{kg}}{\text{hr}}$$

$$C_u := 10 \cdot \frac{\text{tonne}}{\text{hr} \cdot \text{ft}^2}$$

$$C_u = 10 \frac{\text{tonne}}{\text{hr} \cdot \text{ft}^2}$$

$$C_u = 1.076 \times 10^5 \frac{\text{kg}}{\text{hr} \cdot \text{m}^2}$$

$$a_1 := 0.1 \cdot \text{cm}$$

$$d_1 := 0.15 \text{cm}$$

$$a_2 := 2 \cdot \text{cm}$$

$$d_2 := d_1$$

(Perry, 1998)

$$F_{oa} := 100 \cdot \left[ \frac{a_1 \cdot (a_2 + 2 \cdot a_1)}{(a_2 + 2 \cdot a_1 + 3d_2) \cdot (a_1 + d_1)} \right]$$

$$F_{oa} = 33.208$$

$$F_s := 0.065\% \cdot F_{oa}$$

(Perry, 1998)

So, from,

$$A_{\text{screener.1}} := \frac{0.4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s}$$

(Perry, 1998)

$$A_{\text{screener.1}} = 0.103 \text{m}^2$$

The diameter of the screener can be estimated from

$$D_{\text{screener.1}} := \sqrt{\frac{4 \cdot A_{\text{screener.1}}}{\pi}}$$

$$D_{\text{screener.1}} = 0.362 \text{m}$$

Assuming the height to be 1.5 of the diameter,

$$H_{\text{screener.1}} := 1.5 \cdot D_{\text{screener.1}}$$

$$H_{\text{screener.1}} = 0.543 \text{m}$$

## 6.1.4 DESIGN OF CRUSHER

**Type: Gyrotory crusher**

**Material of construction: Steel**

The gyrotory crusher is used to further reduce the size of the limestone to a lesser particle size that could be handled by the Fluidized Bed Furnace.

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 amount of materials in the crusher to be:

$$M' := \begin{pmatrix} 19035.03 \\ 235.48 \\ 353.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \rho := \begin{pmatrix} 2650 \\ 1000 \\ 2250 \\ 2620 \\ 1530.0 \\ 554.0 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3}$$

The average density of the materials in the crusher can be calculated as;

$$\rho_{\text{av}} := \frac{(M'_1 \cdot \rho_1 + M'_2 \cdot \rho_2 + M'_3 \cdot \rho_3 + M'_4 \cdot \rho_4 + M'_5 \cdot \rho_5 + M'_6 \cdot \rho_6)}{(\sum M')} \quad \rho_{\text{av}} = 2623.0004 \frac{\text{kg}}{\text{m}^3}$$

The total mass of the materials in the crusher is given as

$$\sum M' = 19623.74 \frac{\text{kg}}{\text{hr}}$$

So, the volume is calculated to be

$$V_{\text{crusher}} := \frac{\sum M'}{\rho_{\text{av}}} \quad V_{\text{crusher}} = 7.481 \frac{\text{m}^3}{\text{hr}}$$

The volume occupied by the rolls can be 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,

$$d := 1.5 \cdot \text{cm} \quad d = 0.015 \text{ m}$$

$$L := 1.20 \cdot \text{cm} \quad L = 0.012 \text{ m}$$

$$s' := 10 \cdot \frac{\text{cm}}{\text{min}} \quad s' = 1.667 \times 10^{-3} \frac{\text{m}}{\text{s}}$$

$$Q_{\text{crusher}} := \frac{(d \cdot L \cdot s')}{2.96} \quad Q_{\text{crusher}} = 3.649 \times 10^{-4} \frac{\text{m}^3}{\text{hr}}$$

The total volume of the pre-crusher is thus

$$Q_{\text{crusher}} := Q_{\text{crusher}}$$

$$V_{\text{Tcrusher}} := V_{\text{crusher}} + Q_{\text{crusher}} \quad V_{\text{Tcrusher}} = 7.482 \frac{\text{m}^3}{\text{hr}}$$

The volume of the pre-crusher is given as:

$$V = \pi \cdot r^2 \cdot h \quad \text{and, since}$$

$$r = \frac{d}{2} \quad V = \pi \cdot \left(\frac{d}{2}\right)^2 \cdot h \quad V = \pi \cdot \frac{d^2}{4} \cdot h$$

let  $h = kd$ , where  $k$  is a constant

$$\text{substituting for } h, \quad V = \pi \cdot \frac{d^2}{4} \cdot (k \cdot d) \quad 4 \cdot V = k \cdot \pi \cdot d^3$$

Making  $d$  the subject of the formular

$$d = \left(\frac{4 \cdot V}{k \cdot \pi}\right)^{\frac{1}{3}}$$

assuming that  $k := 1.25$

$$V_{\text{Tcrusher}} := V_{\text{Tcrusher}} \cdot \text{hr} \quad \text{From} \quad d_{\text{crusher}} := \left(\frac{4 \cdot V_{\text{Tcrusher}}}{k \cdot \pi}\right)^{\frac{1}{3}}$$

$$d_{\text{crusher}} = 1.968 \text{ m} \quad h_{\text{crusher}} := k \cdot d_{\text{crusher}} \quad h_{\text{crusher}} = 2.46 \text{ m}$$

The area of the pre-crusher is therefore,

$$A := 2\pi \cdot \frac{d_{\text{crusher}}}{2} \cdot h_{\text{crusher}} + 2\pi \cdot \left(\frac{d_{\text{crusher}}}{2}\right)^2 \quad A = 21.291 \text{ m}^2$$

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

$$L = 0.012\text{m}$$

$$K_r := 0.9$$

$$D := d_{\text{crusher}}$$

$$E_2 := 9.5 \cdot W \quad (\text{Ernest, 1995})$$

So, the net power used by the roll is

$$E_{\text{roll}} := [(1.64 \cdot L - 1 \cdot \text{m}) \cdot K_r + 1\text{m}](1.64 \cdot D)^{2.5} \cdot E_2 \cdot \text{m}^{-3.5}$$
$$E_{\text{roll}} = 20.925 \text{ W}$$

## 6.1.5 DESIGN OF SCREENER 2

### Screen Efficiency

A sound method of evaluating screen performance is given by W. S. Tyler, Inc., Mentor, Ohio 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 under 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"      v = "percentage of undersize in the screen oversize"

e = "percentage of undersize in the feed"

### Calculation of screener 2 efficiency

In this project, the efficiency of the screen will be given as

$$E = \frac{R \cdot d}{b} \quad \text{when} \quad R := 80\% \quad d := 11\% \quad b := 9\%$$

Therefore, from

$$E := \frac{R \cdot d}{b} \quad E = 0.978$$

### Estimating Screen Capacity

Various methods of predicting screening capacity have been proposed, and each has its limitations. The throughflow method of Mathews uses the following equation:

$$A = \frac{0.4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s} \quad (\text{Perry, 1998})$$

where

A = "screen area"      C<sub>t</sub> = "throughflow rate"      C<sub>u</sub> = "unit capacity"

F<sub>oa</sub> = "open-area factor"      F<sub>s</sub> = "slotted-area factor"

Given that,

$$m' := \begin{pmatrix} 18749.50 \\ 231.95 \\ 347.93 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad C_t := \sum m' \quad C_t = 1.933 \times 10^4 \frac{\text{kg}}{\text{hr}}$$

$$C_u := 10 \cdot \frac{\text{tonne}}{\text{hr} \cdot \text{ft}^2} \quad C_u = 10 \frac{\text{tonne}}{\text{hr} \cdot \text{ft}^2} \quad C_u = 1.076 \times 10^5 \frac{\text{kg}}{\text{hr} \cdot \text{m}^2}$$

$$a_1 := 0.1 \cdot \text{cm} \quad d_1 := 0.15 \text{cm} \quad a_2 := 2 \cdot \text{cm} \quad d_2 := d_1$$

$$F_{oa} := 100 \cdot \left[ \frac{a_1 \cdot (a_2 + 2 \cdot a_1)}{(a_2 + 2 \cdot a_1 + 3d_2) \cdot (a_1 + d_1)} \right] \quad (\text{Perry, 1998})$$

$$F_{oa} = 33.208 \quad F_s := 0.065\% \cdot F_{oa} \quad (\text{Perry, 1998})$$

So, from,

$$A_{\text{scrainer.2}} := \frac{0.4 \cdot C_t}{C_u \cdot F_{oa} \cdot F_s} \quad (\text{Perry, 1998})$$

$$A_{\text{scrainer.2}} = 0.1 \text{ m}^2$$

## 6.1.6 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 Limestone (raw material). 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 180°C.

$$\text{Amount of water in dryer feed, } W_f := 226.15 \cdot \frac{\text{kg}}{\text{hr}}$$

$$\text{Dry solid in dryer feed, } S_f := 18846.15 \cdot \frac{\text{kg}}{\text{hr}}$$

$$\text{Water content in dryer output, } W_p := 0 \cdot \frac{\text{kg}}{\text{hr}}$$

Hence, water removed by the dryer is

$$W_d := W_f - W_p \quad W_d = 226.15 \frac{\text{kg}}{\text{hr}}$$

$$\text{Inlet air temperature, } T_{ia} := (180 + 273) \cdot \text{K}$$

$$\text{Outlet air temperature, } T_{oa} := (90 + 273) \cdot \text{K}$$

$$\text{Inlet temperature of feed, } T_{if} := (46 + 273) \cdot \text{K}$$

$$\text{Discharge temperature, } T_d := (750 + 273) \cdot \text{K}$$

The temperature of the air leaving the dryer should be selected on the basis of an economic balance between dryer and fuel cost. Dryers are most economically operated when the total Number of Transfer Units (NTU) range from 1.5 to 3.0. Assuming that

So, assuming that

$$\text{NTU} := 2.5$$

Knowing that,

$$\text{NTU} = \ln \left[ \frac{(t_{g1} - t_w)}{(t_{g2} - t_w)} \right]$$

$$t_{g1} := T_{ia} \quad t_w := T_d$$

$$t_{g2} := \frac{(\exp(NTU) \cdot t_w + t_{g1} - t_w)}{\exp(NTU)}$$

$$t_{g2} = 976.212 \text{ K}$$

The heat balance of the dryer has revealed that the total heat required to raise the product to the discharge temperature is

$$Q_t := -1.78 \times 10^{17} \cdot \frac{\text{kJ}}{\text{hr}}$$

$$Q_t = -1.78 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

The Log Mean Temperature Difference (LMTD) across the dryer,  $\Delta T_m$  is

$$\Delta T_m := \left| \frac{[(T_{ia} - T_{if}) - (T_d - T_{oa})]}{\ln \left[ \frac{(T_{ia} - T_{if})}{(T_d - T_{oa})} \right]} \right|$$

$$\Delta T_m = 329.905 \text{ K}$$

The minimum velocity of air is set based on the particle size. Air flow rate of

$$v_{\text{air}} := 23 \times 10^{13} \cdot \frac{\text{kg}}{\text{hr} \cdot \text{m}^2} \text{ is sufficient for lime. Hence this will be used in application.}$$

The minimum velocity is used since it gives the smallest possible size of dryer.

Amount of air required is calculated using the relationship

$$Q_t = M \cdot C_p \cdot \Delta T$$

$$M = \frac{|Q_t|}{(C_p \cdot \Delta T)} \quad \text{Given that} \quad |Q_t| = 1.78 \times 10^{17} \frac{\text{kJ}}{\text{hr}}$$

$$C_p := 4.187 \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \quad \Delta T := T_{ia} - T_{oa} \quad M_{\text{air}} := \frac{|Q_t|}{(C_p \cdot \Delta T)} \quad M_{\text{air}} = 4.724 \times 10^{14} \frac{\text{kg}}{\text{hr}}$$

So,

Area of dryer is thus calculated to be

$$A_{\text{dryer}} := \frac{M_{\text{air}}}{v_{\text{air}}} \quad A_{\text{dryer}} = 2.054 \text{ m}^2$$

Using the formula for the area of dryer which is

$$A_{\text{dryer}} = \pi \cdot R_{\text{dryer}}^2 \quad \text{where } A_{\text{dryer}} \text{ is the area of dryer}$$

$$R_{\text{dryer}} \text{ is the radius of dryer}$$

Denoting the diameter of the dryer as  $D_{\text{dryer}}$

$$A_{\text{dryer}} = \pi \cdot \left( \frac{D_{\text{dryer}}}{2} \right)^2 \quad A_{\text{dryer}} = \pi \cdot \frac{D_{\text{dryer}}^2}{4} \quad 4 \cdot A_{\text{dryer}} = \pi \cdot D_{\text{dryer}}^2 \quad D_{\text{dryer}}^2 = \frac{4 \cdot A_{\text{dryer}}}{\pi}$$



The diameter of dryer is thus equal to

$$D_{\text{dryer}} := \sqrt{\frac{4 \cdot A_{\text{dryer}}}{\pi}}$$

$$D_{\text{dryer}} = 1.617 \text{ m}$$

Length of transfer unit has been related to mass velocity and diameter by the following relation,

$$LTU = 0.0064 \cdot C_p \cdot (G)^{0.84} \cdot d_{\text{dryer}}$$

where G is the mass velocity which is equal to  $G := v_{\text{air}}$ , that is,

$$G = 2.3 \times 10^{14} \frac{\text{kg}}{\text{hr} \cdot \text{m}^2}$$

So,

$$LTU := 194 \cdot 10^{-9} \cdot \frac{C_p}{\text{kJ/kgK}} \cdot \left( \frac{G}{\frac{\text{kg}}{\text{hrm}^2}} \right)^{0.4} \cdot D_{\text{dryer}}$$

$$LTU = 0.73 \text{ m}$$

Length of the dryer is given as:

$$L_{\text{dryer}} := LTU \cdot NTU$$

$$L_{\text{dryer}} = 1.824 \text{ m}$$

### 6.1.7 DESIGN OF FLUIDIZED BED FURNACE

**Parameters:**

**Operating conditions:**

$$P := 1.0 \cdot \text{bar} \quad (\text{Pressure})$$

$$T := 1023.15 \cdot \text{K}$$

(Temperature)

**Reactor:**

Distribution plate is porous Carbon steel

**Feed :**

$$m' := \begin{pmatrix} 18280.76 \\ 0.00 \\ 339.23 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}} \quad \rho := \begin{pmatrix} 2930 \\ 1000 \\ 2250 \\ 2620 \\ 1530.0 \\ 554.0 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3} \quad M_w := \begin{pmatrix} 100.090 \\ 18.016 \\ 60.000 \\ 56.080 \\ 44.010 \\ 16.040 \end{pmatrix} \cdot \frac{\text{kg}}{\text{kmol}} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

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

$$n := \frac{m'}{M_w} \quad n = \begin{pmatrix} 182.643 \\ 0 \\ 5.654 \\ 0 \\ 0 \\ 0 \end{pmatrix} \frac{\text{kmol}}{\text{hr}} \quad \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \\ \text{Natural Gas} \end{pmatrix}$$

$$F := \sum n$$

$$\sum n = 188.297 \frac{\text{kmol}}{\text{hr}} \quad F = 188.297 \frac{\text{kmol}}{\text{hr}}$$

The average density of the components is calculated as;

$$\rho_{\text{av}} := \left( \frac{n_1}{\sum n} \cdot \rho_1 + \frac{n_2}{\sum n} \cdot \rho_2 + \frac{n_3}{\sum n} \cdot \rho_3 + \frac{n_4}{\sum n} \cdot \rho_4 + \frac{n_5}{\sum n} \cdot \rho_5 + \frac{n_6}{\sum n} \cdot \rho_6 \right)$$

$$\rho_{\text{av}} = 2909.582 \frac{\text{kg}}{\text{m}^3}$$

The total mass of the components in the fluidized bed reactor is equal to

$$m_{\text{flow}} := \sum m^i$$

$$V_{\text{flow}} := \frac{m_{\text{flow}}}{\rho_{\text{av}}} \quad V_{\text{flow}} = 6.4 \frac{\text{m}^3}{\text{hr}} \quad (\text{Volumetric flow rate})$$

Composition: 98.19% Limestone and 1.82% Clayey Impurities

### Catalyst: (Fuel Natural Gas)

$$W_{\text{Natural.Gas}} := 100 \cdot \text{kg} \quad (\text{Weight of Natural Gas})$$

$$d_p := 200 \cdot 10^{-6} \cdot \text{m} \quad (\text{Particle diameter of catalyst})$$

$$\phi := \left( \frac{d_p}{6 \cdot \text{m}} \right) \quad (\text{Sphericity of catalyst particle})$$

$$\rho_c := \rho_6$$

$$\rho_c = 554 \text{ kg m}^{-3} \quad [\text{Density of catalyst particle (Natural Gas)}]$$

$$h_s := 38.9 \cdot 10^{-2} \cdot \text{m}$$

**Reaction rate:** The Global rate equation for the fluidized bed decarbonization is given as:

$$r_p = \frac{4 \cdot \pi \cdot r_c^2 \cdot K' \cdot K_e \left( \frac{T_c - T_s}{1 - 2 \cdot \frac{r_s}{r} + \frac{r_s^2}{r^2}} \right)}{M_p} \dots\dots\dots(1)$$

$$T_c = T_s + 25 \dots\dots\dots(2) \quad \text{and} \quad r = r_s - r_c \dots\dots\dots(3)$$

where

- $r_p$  = "Global Rate"       $M_p$  = "Mass of Limestone"       $\Delta H$  = "Change in Enthalpy of the Reaction"
- $D_e$  = "Diffusivity of CO<sub>2</sub> in the Natural Gas Catalyst"       $K_e$  = "Effective thermal conductivity"
- $r$  = "Product layer thickness"       $r_c$  = "Radius of untreated core of CaCO<sub>3</sub>"

$r_s$  = "Radius of CaCO<sub>3</sub> at the surface"     $T_c$  = "Temperature at the core"

$T_s$  = "Surface temperature of the particle"     $K'$  = "Rate constant"

$$r_c := 1.6 \cdot 10^{-5} \text{ m} \quad r_s := 3.2 \cdot 10^{-3} \text{ m}$$

$$r := r_s - r_c \quad (\text{From equation 3}) \quad r = 3.184 \times 10^{-3} \text{ m}$$

$$\text{Also } T_s := (750 + 273.15) \text{ K} \quad T_c := T_s + 25 \text{ K} \quad T_c = 1048.15 \text{ K}$$

$\Delta H$  is obtained from the Energy Balance around the FBR as:

$$\Delta H := 1.056 \cdot 10^7 \frac{\text{kJ}}{\text{hr}} \quad \pi = 3.142$$

$$M_p := m'_1 \quad M_p = 18280.76 \frac{\text{kg}}{\text{hr}}$$

### Fluid properties:

$$\rho_g := 1530 \cdot \frac{\text{kg}}{\text{m}^3} \quad (\text{Density of CO}_2)$$

$$\mu_g := 3.43 \times 10^{-3} \cdot \frac{\text{kg}}{\text{m} \cdot \text{s}} \quad (\text{Viscosity of CO}_2)$$

$D_e$  is calculated using the correlation :

$$D_e = 2.2646 \cdot 10^{-5} \cdot \frac{\sqrt{T \left( \frac{1}{M_a} + \frac{1}{M_b} \right)}}{\sigma_{ab}^2 \cdot \Omega_{D,ab}} \quad (\text{Bird B.R, 2001})$$

where  $\sigma_{ab}$  and  $\epsilon_{ab}$  are called the Lennard Jones parameter of species a and b (i.e. CO<sub>2</sub> and Natural Gas)

and are defined respectively as

$$\sigma_{ab} = \frac{1}{2}(\sigma_a + \sigma_b) \quad \text{and} \quad \epsilon_{ab} = \sqrt{\epsilon_a \cdot \epsilon_b}$$

$\Omega_{D,ab}$  is obtained from a Table of  $\frac{T}{\epsilon_{ab}}$  against the quantity  $\Omega_{D,ab}$

$$M_a := 44.01 \quad M_b := 16.04 \quad \sigma_a := 3.996 \quad \sigma_b := 3.822 \quad \epsilon_a := 190 \quad \epsilon_b := 37 \quad T := 1048.15$$

$$\sigma_{ab} := \frac{1}{2}(\sigma_a + \sigma_b) \quad \sigma_{ab} = 3.909$$

$$\epsilon_{ab} := \sqrt{\epsilon_a \cdot \epsilon_b} \quad \epsilon_{ab} = 83.845 \quad \frac{T}{\epsilon_{ab}} = 12.501$$

$$\text{For } \frac{T}{\epsilon_{ab}} = 12.501 \quad \Omega_{D,ab} := 0.7228$$

$$D_e := 2.2646 \cdot 10^{-5} \cdot \frac{\sqrt{T \cdot \left( \frac{1}{M_a} + \frac{1}{M_b} \right)}}{\sigma_{ab}^2 \cdot \Omega_{D,ab}} \quad D_e = 1.936 \times 10^{-5} \frac{\text{cm}^2}{\text{s}}$$

Hence, Diffusivity of CO<sub>2</sub> :

$$D_e := 1.935 \cdot 10^{-3} \cdot \frac{\text{m}^2}{\text{s}} \quad (\text{Diffusivity of CO}_2)$$

The Effective thermal conductivity is also obtained using the correlation:

$$\mu_a = 2.6693 \cdot 10^{-5} \cdot \frac{\sqrt{M_a \cdot T}}{\sigma_a^2 \cdot \Omega_\mu}$$

and using the viscosity to determine the thermal conductivity, from the Eucken approximation to the thermal conductivity given as

$$K_e = \left( C_p + \frac{5}{4} \cdot R \right) \cdot \frac{\mu_a}{M_a} \quad (\text{Bird B.R, 2001})$$

Given the following:

$$M_a = 44.01 \quad T = 1048.15 \quad R := 8.314 \quad \sigma_a = 3.996 \quad \frac{T}{\epsilon_a} = 5.517$$

$$\text{for } \frac{T}{\epsilon_a} = 5.517 \quad \Omega_\mu := 0.9116$$

$$\mu_a := 2.6693 \cdot 10^{-5} \cdot \frac{\sqrt{M_a \cdot T}}{\sigma_a^2 \cdot \Omega_\mu} \quad \mu_a = 3.938 \times 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{s}}$$

$$C_p := 0.3115 \frac{\text{cal}}{\text{g} \cdot \text{K}} \quad \text{at } 1048.15\text{K}$$

$$K_e := \left( C_p + \frac{5}{4} \cdot R \right) \cdot \frac{\mu_a}{M_a} \quad K_e = 9.579 \times 10^{-5} \frac{\text{cal}}{\text{s} \cdot \text{cm} \cdot \text{K}}$$

Hence the Effective thermal conductivity (in W/m.K) is given as

$$K_e := 0.0 \frac{\text{W}}{\text{m} \cdot \text{K}}$$

To calculate the rate constant K'

Equation of Reaction: CaCO<sub>3</sub> + Heat = CaO + CO<sub>2</sub>

$$\Delta G = R \cdot T \cdot \ln(K') \quad \text{and} \quad K' = \left( \frac{\Delta G}{R \cdot T} \right)^e \quad \frac{\Delta G}{R \cdot T}$$

$$\text{where } \Delta G = \Delta H - T \cdot \Delta S \quad \Delta H := 1.056 \cdot 10^1 \frac{\text{kJ}}{\text{hr}} \quad Q_{\text{fluidized}} := 1.056 \cdot 10^1 \frac{\text{kJ}}{\text{hr}} \quad T := 1173.15$$

$$\Delta S = \frac{Q_{\text{fluidized}}}{T} \quad \Delta S := \frac{Q_{\text{fluidized}}}{T} \quad \Delta S = 9.001 \times 10^{10} \frac{\text{kJ}}{\text{hr} \cdot \text{K}}$$

$$\Delta G := \Delta H - T \cdot \Delta S \quad \Delta G = 0 \quad \frac{\Delta G}{R \cdot T} = 0 \quad K' := e^{\frac{\Delta G}{R \cdot T}} \quad K' = 1$$

Hence the rate constant of the reaction is calculated as : K' = 1

The global rate can thus be computed from the Global rate equation given in Equation (1) above:  
Hence,

$$r_p := \frac{4 \cdot \pi \cdot r_c^2 \cdot K' \cdot K_e \left( \frac{T_c - T_s}{1 - 2 \cdot \frac{r_s}{r} + \frac{r_s^2}{r^2}} \right)}{\Delta H \cdot D_e \cdot M_p}$$

$$r_p = 0.044 \frac{\text{mol}}{\text{kg} \cdot \text{s}}$$

### Geometrical Dimension of the Reactor

The volume of the Reactor is obtained from the relation for Fluidized Bed Reactor given by :

$$W = \frac{F \cdot X_p}{r_p}$$

where  $F$  = "Molar flow rate of Limestone"  $X$  = "Extent of Conversio"  
 $F = 0.052 \text{ mol s}^{-1}$

$$X_p = \frac{W \cdot r_p}{F} \quad X_p := \frac{W \cdot r_p}{F}$$

Hence the extent of conversion:

$$X_p = 0.845$$

Assuming plug flow in the fluidized bed reactor, the performance equation becomes:

$$\frac{V_{\text{reactor}}}{F} = \int \frac{1}{-r_p} dX_p = \int \frac{1}{K' \cdot C_p \cdot (1 - X_p)} dX_p \dots\dots\dots(6)$$

Integrating Equation (6) gives:

$$-\ln(1 - X_p) = \frac{K' \cdot C_p \cdot V_{\text{reactor}}}{F} = \frac{K'(1 - \epsilon_m) \cdot L_m}{u_o} \dots\dots\dots(7)$$

(Levenspiel, 1972)

$$C_p := \frac{F}{V_{\text{flow}}} \quad C_p = 29.424 \text{ mol m}^{-3}$$

$$V_{\text{reactor}} = \frac{-\ln(1 - X_p) \cdot F}{K' \cdot C_p} \quad V_{\text{reactor}} := \frac{-\ln(1 - X_p) \cdot F}{K' \cdot C_p}$$

$$V_{\text{reactor}} = 11.915 \text{ m}^3 \quad V_{\text{reactor}} = 11.915 \text{ m}^3$$

Volume of reactor is given as

$$V_{\text{reactor}} = \pi \cdot R_{\text{reactor}}^2 \cdot H_{\text{reactor}}$$

and

$$R_{\text{reactor}} = \frac{D_{\text{reactor}}}{2} \quad V_{\text{reactor}} = \pi \cdot \left(\frac{D_{\text{reactor}}}{2}\right)^2 \cdot H_{\text{reactor}}$$

$$V_{\text{reactor}} = \pi \cdot \frac{D_{\text{reactor}}^2}{4} \cdot H_{\text{reactor}} \quad \text{assuming that } \frac{H_{\text{reactor}}}{D_{\text{reactor}}} = x$$

then,  $H_{\text{reactor}} = x \cdot D_{\text{reactor}}$

substituting for H,

$$V_{\text{reactor}} = \pi \cdot \frac{D_{\text{reactor}}^2}{4} \cdot (x \cdot D_{\text{reactor}})$$

$$4 \cdot V_{\text{reactor}} = x \cdot \pi \cdot D_{\text{reactor}}^3 \quad D_{\text{reactor}}^3 = \left(\frac{4 \cdot V_{\text{reactor}}}{x \cdot \pi}\right)$$

$$D_{\text{reactor}} = \left(\frac{4 \cdot V_{\text{reactor}}}{x \cdot \pi}\right)^{\frac{1}{3}}$$

taking  $x := 2.5$

$$D_{\text{reactor}} := \left(\frac{4 \cdot V_{\text{reactor}}}{x \cdot \pi}\right)^{\frac{1}{3}} \quad \text{and} \quad H_{\text{reactor}} := x \cdot D_{\text{reactor}}$$

$$D_{\text{reactor}} = 1.824 \text{ m} \quad H_{\text{reactor}} = 4.56 \text{ m}$$

The total surface area is, therefore,

$$A_{\text{reactor}} := 2 \cdot \pi \cdot \frac{D_{\text{reactor}}}{2} \cdot H_{\text{reactor}} + 2 \cdot \pi \cdot \left(\frac{D_{\text{reactor}}}{2}\right)^2 \quad A_{\text{reactor}} = 31.355 \text{ m}^2$$

## 6.1.8 DESIGN OF CYCLONE

Cyclone separators have been used for about 100 years, and are still one of the most widely used of all industrial gas-cleaning devices. The main reasons for the wide-spread use of cyclones are that they are inexpensive to purchase, they have no moving parts, and they can be constructed to withstand harsh operating conditions.

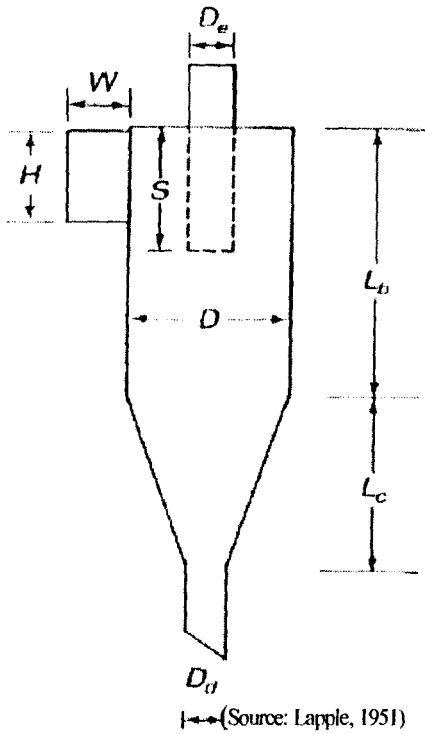
### Standard Cyclone Dimensions

Extensive work has been done to determine in what manner dimensions of cyclones affect performance. In some classic work that is still used today, Shepherd and Lapple (1939, 1940) determined "optimum" dimensions for cyclones. All dimensions were related to the body diameter of the cyclone so that their results could be applied generally. Subsequent investigators reported similar work, and the so-called "standard" cyclones were born. Table 1 summarizes the dimensions of standard cyclones of the three types mentioned previously. Figure 1 illustrates the various dimensions used in Table 1.

**Table 1** Standard cyclone dimensions

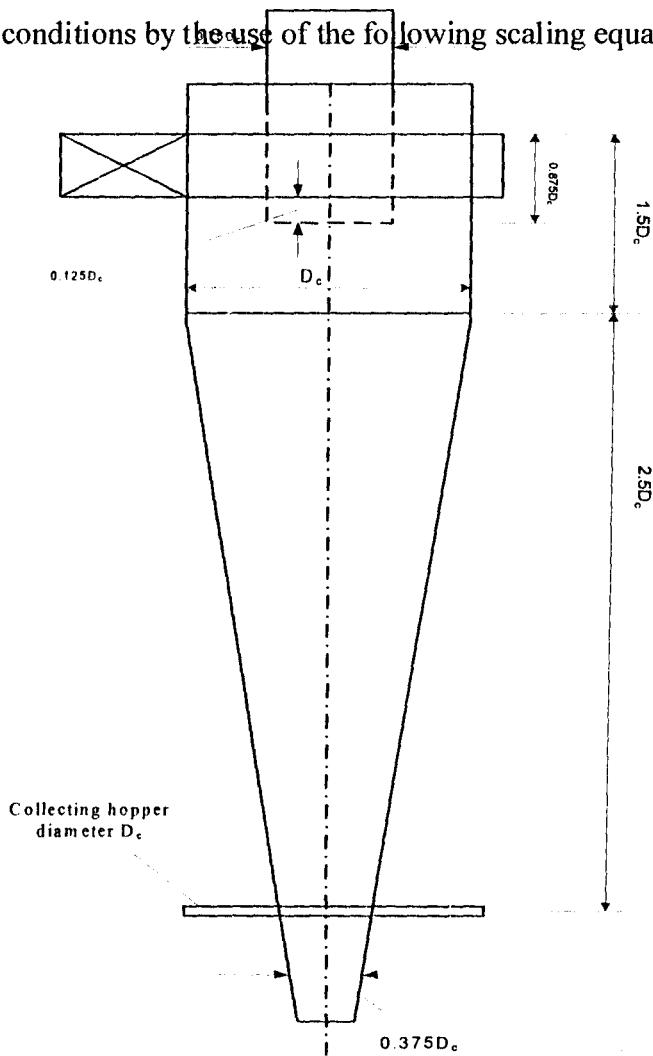
	Cyclone Type					
	High Efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, $D/D$	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, $H/D$	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, $W/D$	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, $D_e/D$	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, $S/D$	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, $L_b/D$	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, $L_c/D$	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, $D_d/D$	0.375	0.4	0.25	0.4	0.375	0.4

SOURCES: Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; columns (3) = Lapple, 1951.



**Fig.1: Cyclone**

Two standard Designs for gas-solid cyclones: a high efficiency cyclone, and a high throughput design were developed by Stairmand. The performance curves for these designs were obtained experimentally under standard test conditions. these curves can then be transformed to other cyclone sizes, and perating conditions by the use of the following scaling equation, for a given separating efficiency:



**Fig (i) High throughput cyclone (High gas rate)**



The scaling equation is given thus:

$$d_2 = d_1 \cdot \left[ \left( \frac{D_{c.2}}{D_{c.1}} \right)^3 \cdot \frac{Q_1}{Q_2} \cdot \frac{\Delta\rho_1}{\Delta\rho_2} \cdot \frac{\mu_1}{\mu_2} \right]^{\frac{1}{2}} \dots\dots\dots(1)$$

(Sinnot R.K., 1999)

where :

$d_1$  = mean diameter of particle separated at the standard conditions at the chosen separating efficiency

$d_2$  = mean diameter of particle separated in the proposed design at the same separating efficiency

$D_{c1}$  = diameter of the standard cyclone = 8inches (203mm)

$D_{c2}$  = diameter of proposed cyclone (mm)

$Q_1$  = Standard flow rate :

for high efficiency design : 223m<sup>3</sup>/hr

for high throughput design : 669m<sup>3</sup>/hr

$Q_2$  = proposed flow rate, m<sup>3</sup>/hr

$\mu_1$  = test fluid viscosity (air at 1atm, 20<sup>0</sup>C)

$$= 0.018\text{mNs/m}^2$$

$\mu_2$  = viscosity, proposed fluid

$\Delta\rho_1$  = solid-fluid density difference in standard conditions = 2000kg/m<sup>3</sup>

$\Delta\rho_2$  = density difference, proposed design

Assuming a separating Efficiency of 90% , the following are obtained from the plots of Grade efficiency against Particle size at standard conditions,

For High gas Rate Cyclone;

at 95% efficiency,  $d_1 := 30 \cdot 10^{-3}\text{mm}$        $Q_1 := 669 \frac{\text{m}^3}{\text{hr}}$        $Q_1 = 669 \frac{\text{m}^3}{\text{hr}}$

$D_{c1} := 203\text{mm}$        $\mu_1 := 0.018 \cdot 10^{-3} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$        $\mu_1 = 1.8 \times 10^{-5} \text{kg m}^{-1} \text{s}^{-1}$        $\Delta\rho_1 := 2000 \frac{\text{kg}}{\text{m}^3}$

(Sinnot R.K., 1999)

**From the Material, Energy Balance and the momentum Balance the following data are obtained :**

mean diameter of particle size :  $d_2 := 0.5\text{mm}$       viscosity:  $\mu_2 := 0.0293 \frac{\text{kg}}{\text{m} \cdot \text{s}}$

proposed flow rate :  $M' := 9984.13 \frac{\text{kg}}{\text{hr}}$        $\rho_{\text{particle}} := \rho_{\text{av}}$        $\rho_{\text{particle}} = 2909.582 \text{kg m}^{-3}$

$Q_2 := \frac{M'}{\rho_{\text{particle}}}$        $Q_2 = 3.431 \frac{\text{m}^3}{\text{hr}}$        $\rho_{\text{Natural.Gas}} := 554.0 \frac{\text{kg}}{\text{m}^3}$

$\Delta\rho_2 := \rho_{\text{particle}} - \rho_{\text{Natural.Gas}}$        $\Delta\rho_2 = 2355.582 \text{kg m}^{-3}$

Hence to obtain the proposed cyclone diameter, we make  $D_{c2}$  the subject in Equation (i) :

$$\frac{D_{c,2}}{D_{c,1}} = \left[ \left( \frac{d_2}{d_1} \right)^2 \cdot \left( \frac{Q_2}{Q_1} \cdot \frac{\Delta\rho_2}{\Delta\rho_1} \cdot \frac{\mu_2}{\mu_1} \right) \right]^{\frac{1}{3}} \quad D_{c,2} = D_{c,1} \cdot \left[ \left( \frac{d_2}{d_1} \right)^2 \cdot \left( \frac{Q_2}{Q_1} \cdot \frac{\Delta\rho_2}{\Delta\rho_1} \cdot \frac{\mu_2}{\mu_1} \right) \right]^{\frac{1}{3}} \quad \dots\dots\dots(ii)$$

Equation (ii) is used to compute the proposed cyclone diameter :

$$D_{c2} := D_{c1} \cdot \left[ \left( \frac{d_2}{d_1} \right)^2 \cdot \left( \frac{Q_2}{Q_1} \cdot \frac{\Delta\rho_2}{\Delta\rho_1} \cdot \frac{\mu_2}{\mu_1} \right) \right]^{\frac{1}{3}} \quad D_{c2} = 2.838 \text{ m}$$

Hence the Diameter of the required Cyclone is: **2.838m**

This is too large compared to the standard diameter of **0.203m**, Hence we try three cyclones in parallel

Hence  $D_{c2} = 0.95\text{m}$

Hence the dimension of each of the 4 cyclones is as shown below:

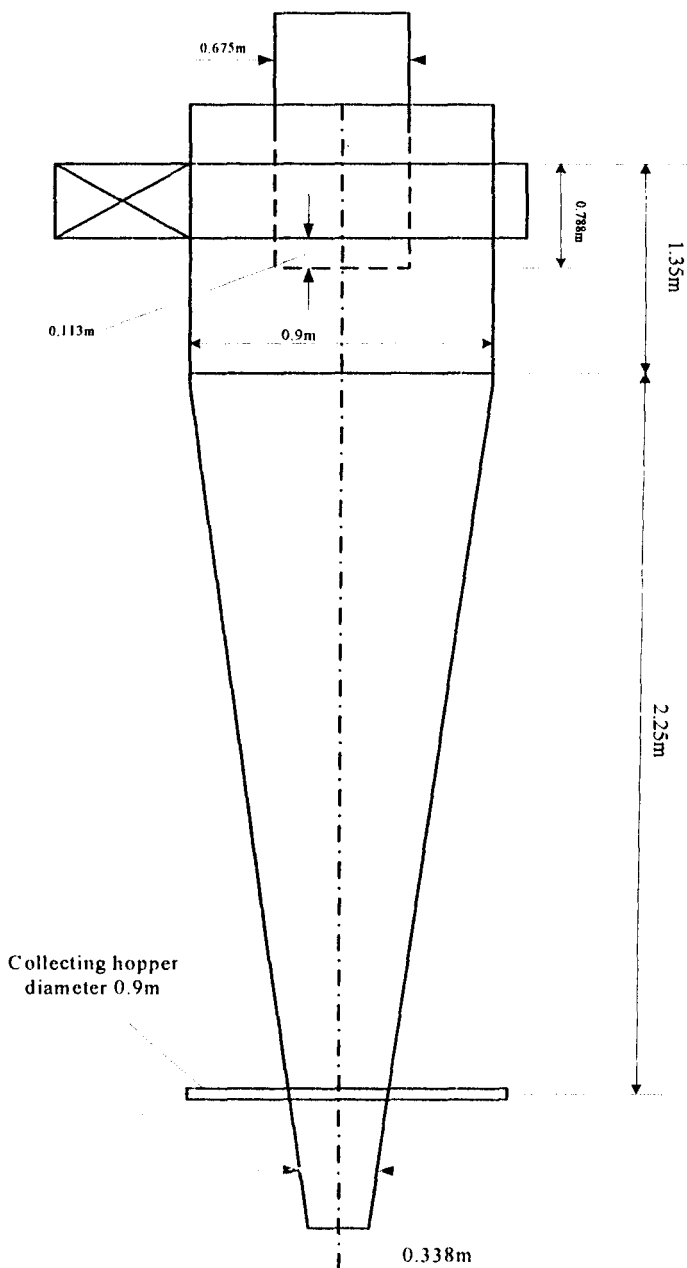


Fig (ii) Proposed Cyclone Design (with Dimensions)

A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency. In this model, gas spins through a number of revolutions  $N_e$  in the outer vortex. The value of  $N_e$  can be approximated by

$$N_e = \frac{1}{H} \left( L_b + \frac{L_c}{2} \right) \dots\dots\dots(iii)$$

where:

$N_e$  = number of effective turns in each cyclone      $H$  = height of inlet duct (m or ft)  
 $L_b$  = length of cyclone body (m or ft)              $L_c$  = length (vertical) of cyclone cone (m or ft).

From Fig (i) and (ii) and Table 1

$$H := 0.375 \cdot D_{c2} \qquad L_c := 1.5 \cdot D_{c2} \qquad L_b := 2.5 \cdot D_{c2}$$

$$N_e := \frac{1}{H} \left( L_b + \frac{L_c}{2} \right) \qquad N_e = 9$$

To be collected, particles must strike the wall within the amount of time that the gas travels in the outer vortex. The *gas residence time* in the outer vortex is

$$\Delta t = \pi D_{c2} \cdot \frac{N_e}{V'} \dots\dots\dots(iv)$$

Where :

$\Delta t$  = time spent by gas during spiraling descent (sec)      $D_{c2}$  = cyclone body diameter (m or ft)  
 $V_i$  = gas inlet velocity (m/s or ft/s) =  $Q/WH$               $Q$  = volumetric inflow (m<sup>3</sup>/s or ft<sup>3</sup>/s)  
 $W$  = width of inlet (m or ft).

$$V' := \frac{Q_2}{H \cdot W} \qquad \text{Where: } D_{c2} := 0.95\text{m} \qquad W := 0.75D_{c2}$$

$$Q_2 = 3.431 \frac{\text{m}^3}{\text{hr}} \qquad H = 1.064\text{m} \qquad W = 0.712\text{m}$$

$$V' = 1.257 \times 10^{-3} \frac{\text{m}}{\text{s}} \qquad V' := V'$$

$$\Delta t := \frac{\pi D_{c2} \cdot N_e}{4V'} \qquad \Delta t = 1.429\text{hr}$$

Residence time in each cyclone:

$$\Delta t_{\text{cyclone}} := \frac{\Delta t}{3} \qquad \Delta t_{\text{cyclone}} = 28.576\text{min}$$

### 6.1.9 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. The aim here is to reduce the temperature of lime from 303K to 373K.

#### SPECIFICATIONS

**Heat capacity coefficients:**

$$\text{Data} := \begin{pmatrix} 82.34 & 4.975 \cdot 10^{-2} & -12.87 \cdot 10^{10} \cdot 10^{-5} & 0 \\ 18.2964 & 47.212 \cdot 10^{-2} & -133.88 \cdot 10^{-5} & 1314.2 \cdot 10^{-9} \\ 15.2 & 2.68 \cdot 10^{-2} & 0 & 0 \\ 41.84 & 2.03 \cdot 10^{-2} & -4.52 \cdot 10^{10} \cdot 10^{-5} & 0 \\ 36.11 & 4.233 \cdot 10^{-2} & -2.887 \cdot 10^{-5} & 7.464 \cdot 10^{-9} \end{pmatrix} \begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \end{pmatrix}$$

$$\begin{pmatrix} \text{CaCO}_3 \\ \text{H}_2\text{O} \\ \text{Impurities} \\ \text{CaO} \\ \text{CO}_2 \end{pmatrix} m_w := \begin{pmatrix} 100.09 \\ 18.016 \\ 60.00 \\ 56.08 \\ 44.01 \end{pmatrix} \cdot \frac{\text{kg}}{\text{kmol}} \quad m' := \begin{pmatrix} 2742.11 \\ 0.00 \\ 3392.31 \\ 501889.03 \\ 0.00 \end{pmatrix} \cdot \frac{\text{kg}}{\text{hr}}$$

$$T_{\text{in}} := (250 + 273) \cdot \text{K}$$

$$T_{\text{out}} := (150 + 273) \cdot \text{K}$$

$$T_b := \frac{T_{\text{in}} + T_{\text{out}}}{2}$$

$$T_b = 473 \text{ K}$$

At this temperature, the specific capacity of fatty acids product is given as

$$a_b := \text{Data}_{1,1}$$

$$b_b := \text{Data}_{1,2}$$

$$c_b := \text{Data}_{1,3}$$

$$d_b := \text{Data}_{1,4}$$

$$a_b = 82.34 \quad b_b = 0.05 \quad c_b = -1.287 \times 10^6 \quad d_b = 0$$

$$C_p := \left[ a_b + b_b \cdot \frac{T_b}{K} + c_b \cdot \left( \frac{T_b}{K} \right)^2 + d_b \cdot \left( \frac{T_b}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$$

$$C_p = -2.879 \times 10^{11} \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$$

$$n_{\text{comp}} := \sum \left( \frac{\text{m}^3}{\text{m}^3} \right) \quad n_{\text{comp}} = 9033.454 \frac{\text{kmol}}{\text{hr}}$$

$$\text{Heat\_duty} := n_{\text{comp}} \cdot C_p \cdot (T_{\text{out}} - T_{\text{in}})$$

$$\text{Heat\_duty} = 7.225 \times 10^{13} \text{ kW}$$

$$Q := \text{Heat\_duty}$$

$$Q = 7.225 \times 10^{13} \text{ kW}$$

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

$$a_w := \text{Data}_{3,1} \quad b_w := \text{Data}_{3,2} \quad c_w := \text{Data}_{3,3} \quad d_w := \text{Data}_{3,4}$$

$$a_w = 15.2 \quad b_w = 0.027 \quad c_w = 0 \quad d_w = 0$$

$$T_w := (35 + 273) \cdot \text{K}$$

$$c_{pw} := \left[ a_w + b_w \cdot \frac{T_w}{K} + c_w \cdot \left( \frac{T_w}{K} \right)^2 + d_w \cdot \left( \frac{T_w}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$c_{pw} = 23.454 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

## PHYSICAL PROPERTIES:

### LIME

Heat capacities of the lime at the inlet, outlet and mean condition:

$$T_{bi} := T_{in} \quad T_{bo} := T_{out} \quad T_{bm} := T_b$$

$$c_{pbi} := \left[ a_b + b_b \cdot \frac{T_{bi}}{K} + c_b \cdot \left( \frac{T_{bi}}{K} \right)^2 + d_b \cdot \left( \frac{T_{bi}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kmol} \cdot K}$$

$$c_{pbi} = -3.52 \times 10^{11} \frac{\text{kJ}}{\text{kmol} \cdot K}$$

$$c_{pbo} := \left[ a_b + b_b \cdot \frac{T_{bo}}{K} + c_b \cdot \left( \frac{T_{bo}}{K} \right)^2 + d_b \cdot \left( \frac{T_{bo}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kmol} \cdot K}$$

$$c_{pbo} = -2.303 \times 10^{11} \frac{\text{kJ}}{\text{kmol} \cdot K}$$

$$c_{pbm} := \left[ a_b + b_b \cdot \frac{T_{bm}}{K} + c_b \cdot \left( \frac{T_{bm}}{K} \right)^2 + d_b \cdot \left( \frac{T_{bm}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kmol} \cdot K}$$

$$c_{pbm} = -2.879 \times 10^{11} \frac{\text{kJ}}{\text{kmol} \cdot K}$$

Therefore, the properties of fatty acids at the inlet, outlet and mean conditions are

$$\begin{pmatrix} \text{Inlet} \\ \text{Mean} \\ \text{Outlet} \end{pmatrix} T_{\text{comp}} := \begin{pmatrix} T_{bi} \\ T_{bm} \\ T_{bo} \end{pmatrix} \quad c_{p\_comp} := \begin{pmatrix} c_{pbi} \\ c_{pbm} \\ c_{pbo} \end{pmatrix} \quad k_{\text{comp}} := \begin{pmatrix} 0.0413 \\ 0.0324 \\ 0.0355 \end{pmatrix} \cdot \frac{W}{m \cdot K}$$

$$\rho_{\text{comp}} := \begin{pmatrix} 840 \\ 844 \\ 846 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\mu_{\text{comp}} := \begin{pmatrix} 9.707 \\ 10.233 \\ 10.003 \end{pmatrix} \cdot \text{mN} \cdot \text{s} \cdot \text{m}^{-2}$$

## WATER

Heat capacities of the water at the inlet, outlet and mean condition:

$$T_{wi} := (35 + 273) \cdot K$$

$$T_{wo} := (90 + 273) \cdot K$$

$$T_{wm} := \frac{T_{wi} + T_{wo}}{2}$$

$$c_{pwi} := \left[ a_w + b_w \cdot \frac{T_{wi}}{K} + c_w \cdot \left( \frac{T_{wi}}{K} \right)^2 + d_w \cdot \left( \frac{T_{wi}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kg} \cdot K}$$

$$c_{pwi} = 23.454 \frac{\text{kJ}}{\text{kg} \cdot K}$$

$$c_{pwo} := \left[ a_w + b_w \cdot \frac{T_{wo}}{K} + c_w \cdot \left( \frac{T_{wo}}{K} \right)^2 + d_w \cdot \left( \frac{T_{wo}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kg} \cdot K}$$

$$c_{pwo} = 24.928 \frac{\text{kJ}}{\text{kg} \cdot K}$$

$$c_{pwm} := \left[ a_w + b_w \cdot \frac{T_{wm}}{K} + c_w \cdot \left( \frac{T_{wm}}{K} \right)^2 + d_w \cdot \left( \frac{T_{wm}}{K} \right)^3 \right] \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$c_{pwm} = 24.191 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

In summary, the properties of water at the inlet, outlet and mean conditions are

$$T_{\text{water}} := \begin{pmatrix} T_{wi} \\ T_{wm} \\ T_{wo} \end{pmatrix} \quad c_{p\_water} := \begin{pmatrix} c_{pw} \\ c_{pwm} \\ c_{pwo} \end{pmatrix} \quad k_{\text{water}} := \begin{pmatrix} 0.59 \\ 0.60 \\ 0.61 \end{pmatrix} \cdot \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$\rho_{\text{water}} := \begin{pmatrix} 980 \\ 990 \\ 1000 \end{pmatrix} \cdot \frac{\text{kg}}{\text{m}^3} \quad \mu_{\text{water}} := \begin{pmatrix} 0.8 \\ 0.85 \\ 0.9 \end{pmatrix} \cdot 10^{-3} \cdot \text{N} \cdot \text{s} \cdot \text{m}^{-2}$$

## OVERALL COEFFICIENT

For a cooler of this type, the overall coefficient will be in the range 300 to 500 W/m<sup>2</sup>oC,

Figure 12.1 and Table 12.1 (Richardson and Coulson); taking  $U := 500 \cdot \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$

## 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,

$$\Delta T_{lm} := \left| \frac{(T_{\text{water}_1} - T_{\text{comp}_1}) - (T_{\text{water}_3} - T_{\text{comp}_3})}{\ln \left[ \frac{(T_{\text{water}_1} - T_{\text{comp}_1})}{(T_{\text{water}_3} - T_{\text{comp}_3})} \right]} \right| \quad \Delta T_{lm} = 121.445 \text{ K}$$

$$R := \frac{T_{\text{water}_1} - T_{\text{water}_3}}{T_{\text{comp}_3} - T_{\text{comp}_1}} \quad R = 0.55 \quad R = \text{"dimensionless temperature ratio"}$$

$$S := \frac{T_{\text{comp}_3} - T_{\text{comp}_1}}{T_{\text{water}_1} - T_{\text{comp}_1}} \quad S = 0.465 \quad S = \text{"dimensionless temperature ratio"}$$

From Figure 12.19,  $F_t := 7 \cdot 10^9$ , which is acceptable.

$$\text{So,} \quad \Delta T_m := F_t \cdot \Delta T_{lm} \quad \Delta T_m = 8.501 \times 10^{11} \text{ K}$$

### HEAT TRANSFER AREA

From the formula given as

$$Q = U \cdot A \cdot \Delta T_m$$

$$A_{\text{cooler}} := \frac{|Q|}{U \cdot \Delta T_m}$$

$$A_{\text{cooler}} = 169.982 \text{ m}^2$$

### 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.  $D_o := 19.05\text{mm}$ ), 14.83 mm inside diameter (i.e.  $D_i := 14.83\text{mm}$ ), 5 m long tubes (i.e.  $L := 5\text{m}$ ) (a popular size) on a triangular 23.81 mm (i.e.  $p_t := 23.81 \cdot \text{mm}$ ) pitch (pitch/dia. = 1.25).

### NUMBER OF TUBES

Area of one tube (neglecting thickness of tube sheets) is given thus;

$$A_{\text{one\_tube}} := \pi \cdot D_o \cdot L \quad A_{\text{one\_tube}} = 0.299 \text{ m}^2$$



Number of tubes

$$N_t := \frac{A_{\text{cooler}}}{A_{\text{one\_tube}}} \quad N_t = 568.05$$

So, for two passes, tubes per pass is

$$\text{tube\_per\_pass} := \frac{N_t}{2} \quad \text{tube\_per\_pass} = 284.026$$

Check the tube-side velocity at this stage to see if it looks reasonable.

$$A_{\text{tube}} := \frac{\pi}{4} \cdot (D_i)^2 \quad A_{\text{tube}} = 0.0001727 \text{ m}^2$$

So,

$$\text{area\_per\_pass} := \text{tube\_per\_pass} \cdot A_{\text{tube}} \quad \text{area\_per\_pass} = 0.049 \text{ m}^2$$

$$m_{\text{water}} := 85000 \cdot \frac{\text{kg}}{\text{hr}}$$

$$\text{Volumetric\_flow}_t := m_{\text{water}} \cdot \frac{1}{\rho_{\text{water}_2}} \quad \text{Volumetric\_flow}_t = 85.859 \frac{\text{m}^3}{\text{hr}}$$

$$\text{Tube side velocity, } u_t := \frac{\text{Volumetric\_flow}_t}{\text{area\_per\_pass}} \quad u_t = 0.486 \frac{\text{m}}{\text{s}}$$

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,  $K_1 := 0.249$ ,  $n_1 := 2.207$

$$D_b := D_o \cdot \left( \frac{N_t}{K_1} \right)^{\frac{1}{n_1}} \quad D_b = 0.633 \text{ m}$$

For a split-ring floating head exchanger the typical shell clearance from Figure 12.10 (Richardson)

and Coulson) is 56 mm (i.e.  $S_c := 56 \cdot \text{mm}$ ), so the shell inside diameter,

$$D_s := D_b + S_c \quad D_s = 0.689 \text{ m}$$

### TUBE-SIDE HEAT TRANSFER COEFFICIENT

$$\text{Re} = \frac{G_s \cdot d_e}{\mu} = \frac{u_s \cdot d_e \cdot \rho}{\mu}$$

$$\text{Re} := \frac{\rho_{\text{water}_2} \cdot u_t \cdot D_i}{\mu_{\text{water}_2}} \quad \text{Re} = 8396.694$$

$$\text{Pr} = \frac{c_p \cdot \mu}{k}$$

$$\text{Pr} := \frac{c_{p\_water_2} \cdot \mu_{water_2}}{k_{water_2}} \quad \text{Pr} = 34.271$$

$$\frac{L}{D_i} = 337.154$$

$$\mu := 0.99 \text{ N} \cdot \text{m} \cdot \text{s}^{-2}$$

$$\mu_w := 1 \cdot (\text{N} \cdot \text{m} \cdot \text{s}^{-2})$$

From figure 12.23 (Richardson and Coulson),  $j_h := 3.2 \cdot 10^{-3}$

$$\text{Nu} := j_h \cdot \text{Re} \cdot \text{Pr}^{\frac{1}{3}} \cdot \left( \frac{\mu}{\mu_w} \right)^{0.14} \quad \text{Nu} = 87.155$$

$$h_i := \text{Nu} \cdot \left( \frac{k_{water_2}}{D_i} \right) \quad h_i = 3526.146 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

This is clearly too low if  $U_o$  is to be  $370 \text{ W/m}^2\text{oC}$ . The tube-side velocity 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.

$$u_t := 2 \cdot u_t$$

$$u_t = 0.972 \frac{\text{m}}{\text{s}}$$

$$\text{Re} := 2 \cdot \text{Re}$$

$$\text{Re} = 1.679 \times 10^4$$

$$j_h := 3.8 \cdot 10^{-3}$$

$$\text{Nu} := j_h \cdot \text{Re} \cdot P_r^3 \cdot \left( \frac{\mu}{\mu_w} \right)^{0.14}$$

$$\text{Nu} = 206.992$$

$$h_i := \text{Nu} \cdot \left( \frac{k_{\text{water}_2}}{D_i} \right)$$

$$h_i = 8374.596 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

### SHELL-SIDE HEAT TRANSFER COEFFICIENT

Using Kern's method,

For 4 passes,  $K_1 := 0.175$  and  $n_1 := 2.285$

$$D_b := D_o \cdot \left( \frac{N_t}{K_1} \right)^{\frac{1}{n_1}}$$

$$D_b = 0.656 \text{ m}$$

The bundle to shell clearance is still around 56 mm, giving:

$$D_s := D_b + S_c$$

$$D_s = 0.712 \text{ m}$$

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.

$$A_s := \frac{(p_t - D_o) \cdot D_s \cdot l_b}{p_t}$$

$$A_s = 0.02024 \text{ m}^2$$

$$d_e := \frac{1.10}{D_o} \cdot (p_t^2 - 0.917 \cdot D_o^2) \quad d_e = 0.01352 \text{ m}$$

Volumetric flow-rate on shell-side

$$\text{Volumetric\_flow}_s := \frac{n_{\text{comp}} \cdot \text{mw}_5}{\rho_{\text{comp}_2}} \quad \text{Volumetric\_flow}_s = 1.131 \times 10^4 \frac{\text{m}^3}{\text{day}}$$

Shell-side velocity

$$u_s := \frac{\text{Volumetric\_flow}_s}{A_s} \quad u_s = 6.464 \frac{\text{m}}{\text{s}}$$

$$\text{Re} := \frac{\rho_{\text{comp}_2} \cdot u_s \cdot D_i}{\mu_{\text{comp}_2}} \quad \text{Re} = 7906.423$$

$$\text{Pr} := \frac{c_{p\_comp_2} \cdot \mu_{\text{comp}_2}}{k_{\text{comp}_2} \cdot \text{mw}_5} \quad \text{Pr} = -2.066 \times 10^{12}$$

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 (Richardson and Coulson),  $j_h := 4.52 \cdot 10^{-3}$ .

Neglecting the viscosity correction

$$h_s := \frac{k_{\text{comp}_2}}{d_e} \cdot j_h \cdot \text{Re} \cdot \text{Pr}^3 \quad h_s = 5.454 \times 10^5 + 9.447i \times 10^5 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

$$f_{\text{water}} := 2857.14 \cdot \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \quad f_{\text{comp}} := 5000 \cdot \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

$$\text{OVERALL COEFFICIENT} \quad U_o := \left[ \left( \frac{1}{h_i} + \frac{1}{f_{\text{water}}} \right) \cdot \frac{D_o}{D_i} + \frac{D_o \cdot \ln\left(\frac{D_o}{D_i}\right)}{k_{\text{comp}_2}} + \frac{1}{h_s} + \frac{1}{f_{\text{comp}}} \right]^{-1} \quad U_o = 8.664 + 5.959i \times 10^{-5} \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

## PRESSURE DROP

### TUBE SIDE

240 tubes, 4 passes,  $D_i = 0.0148 \text{ m}$  ,  $u_t = 0.972 \text{ m s}^{-1}$  ,  $Re = 7906.423$  . From Figure

12.24 (Richardson and Coulson),  $j_f := 5 \cdot 10^{-3}$ .

$$\Delta P_t := 4 \cdot 8 \cdot j_f \cdot \left( \frac{D_s}{d_e} \right) \cdot \left( \frac{L}{l_b} \right) \cdot \frac{\rho_{\text{water}_2} \cdot u_s^2}{2} \cdot \left( \frac{\mu}{\mu_w} \right)^{-0.14}$$

$$\Delta P_t = 6.128 \times 10^6 \frac{\text{N}}{\text{m}^2}$$

## CHAPTER SEVEN

### 7.0 OPTIMIZATION OF REACTOR

#### 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.

Given the following :

$$K' := 1 \quad K_e := 0.04 \quad \Delta H := 1.056 \quad D_e := 1.936 \cdot 10^{-5} \quad P := 101325 \quad R_g := 8.314 \quad T_s := 1023.15$$

$$r_s := 3.2 \cdot 10^{-2} \quad r_c := 1.6 \cdot 10^{-5} \quad r := r_s - r_c \quad T_c := T_s + 25 \quad M_p := 18280.76 \quad \pi := 3.142$$

$$r_p := \frac{4 \cdot \pi \cdot r_c^2 \cdot K' \cdot K_e \left( \frac{T_c - T_s}{1 - 2 \cdot \frac{r_s}{r} + \frac{r_s^2}{r^2}} \right)}{M_p} \quad r_p = 0.034$$

To optimize the reactor means to either maximize the rate of conversion of the limestone to quicklime or to minimize the cost of the reactor.

Hence, maximizing:

$$r_p(r_s, r, r_c, T_s, T_c, M_p) := \frac{4 \cdot \pi \cdot r_c^2 \cdot K' \cdot K_e \left( \frac{T_c - T_s}{1 - 2 \cdot \frac{r_s}{r} + \frac{r_s^2}{r^2}} \right)}{M_p}$$

Given the following Conditions:

$$r_s \leq 3.2 \cdot 10^{-2} \quad r \geq 3.184 \cdot 10^{-3} \quad T_c \leq 1173.15 \quad M_p \leq 18280.76 \quad T_s \geq 1023.15$$

$$\begin{pmatrix} r_s \\ r \\ r_c \\ T_c \\ T_s \\ M_p \end{pmatrix} := \text{Maximize}(r_p, r, r_c, T_s, T_c, M_p, \Delta H) \quad \begin{pmatrix} r_s \\ r \\ r_c \\ T_c \\ T_s \\ M_p \end{pmatrix} = \begin{pmatrix} 0.008 \\ 0.008 \\ 258.908 \\ 523.661 \\ 4601.696 \\ 0.525 \end{pmatrix}$$

Hence the optimum rate of reaction,  $r_p$  is obtained at the following values of :

$$\begin{pmatrix} r_s \\ r \\ r_c \\ T_c \\ T_s \\ M_p \end{pmatrix} = \begin{pmatrix} 0.008 \\ 0.008 \\ 258.908 \\ 523.661 \\ 4601.696 \\ 0.525 \end{pmatrix}$$

## 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 must 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, cutout 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 must 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 Control Mechanism

The pneumatic control hardware is recommended for this process it will be powered by instrument air supplies.

The control mechanism for this process consist of a sensor to detect the process variables; a transmitter to convert the sensor into an equivalent "signal" a controller that compares this process signal with a desired set point value and produces an appropriate controller output signal and a final control element

(pneumatic activator) that changes the manipulated variable with the use of a mechanical action.

### **9.3 Control Sensors**

The devices to be used for the on-line measurement of the process variables are:

- 1) Flow sensor: The orifice meter can be employed in the process since it is simple and of low cost.
- 2) Temperature sensor: The recommended temperature sensors are resistance thermometer detectors (RTDS) and Thermocouples. The 100v pt (-2000C to 850C) and type N (0-13000) are both sufficient for RTDS and thermocouples respectively.
- 3) Pressure sensors: Bourdon – Tube pressure gauge can be used.
- 4) Level sensor: float activated devices are sufficient.

Alarms are to be employed to alert the process operator to a process that requires immediate action and attention. Instead of individually issuing point alarms, all alarms associated with a certain aspect of the process are to be simply wired to give a single trouble alarm.

### **9.4 Transmitters, Controllers and Control Valves**

The transmitter is the interphase between the process and its control system. The transmitter converts the sensors signal into a control signal. The pilot – acting controllers should be employed in the process. The pilot – acting controllers are capable of greater degree of sensitivity since they eliminate of the lags which would be inherent in self – acting mechanism activated by the force of a large

volume of fluid. The fluid control element is an automatic control which throttles the flow of the manipulated variable.

## **9.5 Process Control of Equipments**

### **9.5.1 Process control of fluidized bed furnace**

The purpose of the fluidized bed furnace is very simple: To decarbonize the calcium carbonate. Its representation on a process flow diagram is also very simple. But, of course, fluidized bed reactors 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. The figure below shows the piping and instrumentation diagram for the quicklime plant.

## CHAPTER TEN

### 10.0 ENVIRONMENTAL ACCEPTABILITY

#### 10.1 Identification of possible pollutants

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.

Carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and nitrogen oxides (NO) are all produced in furnaces. Sulfur dioxide emissions are influenced by several factors, including the sulfur content of the fuel, the sulfur 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 sulfur emissions is the furnace's fuel, and the vast majority of the fuel sulfur is not emitted because of reactions



with calcium oxides in the furnace. Sulfur dioxide emissions may be further reduced if the pollution equipment uses a wet process or if it brings CaO and SO into intimate contact.

Carbon dioxide is emitted from the furnace as a result of the carbonate in the limestone being reduced to CO gas, and the carbon in the fuel oxidizing. If CO emissions from the fuel combustion are estimated, only non-combustion CO emission factors should be used.

Other particulate sources in lime plants include primary and secondary crushers, mills, screens, mechanical and pneumatic transfer operations, storage piles, and roads. If quarrying is a part of the lime plant operation, particulate emissions may also result from drilling and blasting.

#### **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 NORMAL START UP AND SHUT DOWN OF LIME PLANT

Before start up or shut down of any process plant the checkout phase which is the transient state from plant construction to plant operation must be put into consideration. This phase focuses on the validation of component and sub system operations to avoid unnecessary start up delays. The process hazard review are also considered during this phase.

The start up and shut down procedures which are usually provided by the operation personnel should be flexible enough to be carried out in several ways. The operating limits of the plant must not be exceed and dangerous mixtures must be eliminated.

Abnormal states of concentration, temperature, pressure reactants, and products must be controlled.

Contaminants often enter the system at this stage. Therefore, care must be taken to avoid water and other material condensing in unplanned location causing process level to get out of control.

#### 11.1 Start up procedure

For the lime plant designed, the following are the start up procedures:

- I. The source should be open to be supplied to the fluidized bed decarbonisation 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 valve 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 lime to the furnace should be stopped
- ii. The supply of fuel to the furnace should be cut off:

All the purge valves should be opened to discharge unconverted products.

## 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 outlined below. (Sinnot R K, 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.

##### 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 natural gas); where this is also close to the marketing area.

##### 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 two 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.

#### **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.

#### **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.

#### **12.1.6 Environmental impact and effluent disposal**

All industrial processes produce waste products, and full consideration must be given to the difficulties and cost of their disposal. The disposal of toxic and harmful effluents will

be covered by local regulations, and the appropriate authorities must be consulted during the initial site survey to determine the standards that must be met.

#### **12.1.7 Local community considerations**

The proposed lime plant must be fit in with and be acceptable to the local community. Full consideration must be given to the safe location of the lime plant so that it does not impose a significant additional risk to the community.

On a new site, the local community must be able to provide adequate facilities for the lime plant personnel: schools, banks, housing, and recreational and cultural facilities.

#### **12.1.8 Availability of suitable land (site considerations)**

Sufficient suitable land be available for the proposed lime plant and for future expansion. The land should be ideally flat, well drained and have suitable load bearing capacity. A full site evaluation should be made to determine the need for piling or other special foundations. It should also be available at low cost.

#### **12.1.9 Climate**

Adverse climatic conditions at a site will increase costs. Abnormally low temperatures will require the provision of additional insulation & special heating for equipment & pipe runs. Stronger structures will be needed at locations subject to high winds or earthquakes.

#### **12.1.10 Political and strategic consideration**

Capital grants, tax concessions and other incentives provided by governments to direct new investment to preferred locations, such as areas of high un-employment should be the overriding considerations in the site selection.

## **12.2 Selection of Site**

Abeokuta in Ogun State is chosen for as the selected site for lime production plant. The selection has been based on some requirements, which the site was able to meet among the factors for the site selection. The reasons for choosing the site are outlined below.

## **12.3 Justification of the Selected Site**

### **12.3.1 Availability of raw materials**

One of the major raw materials in the production of lime is the phosphate gypsum. This raw material has been discovered to be abundant in Abeokuta in Ogun State.

### **12.3.2 Transport**

Regarding the transport facilities, Abeokuta is close to seaport and a waterway. Besides, it is close to a major airport. So, 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 Abeokuta has good road network.

### **12.3.3 Availability of labour**

For the fact that Abeokuta is located in an south-western region, youths, both skilled and unskilled, are now trooping into the area to seek their source of living. That is to say, all kinds of labour force are available there.

### **12.3.4 Climate**

The absence of adverse climatic conditions such as too low temperature or too high wind loads or earthquakes has made Abeokuta a good site for the lime plant.



### **12.3.5 Political and strategic considerations**

In an attempt to woo investors to Ogun State, the Ogun State government has given capital grants and other inducements to direct new investment to Ogun State. Thus, availability of such grants is an overriding consideration in selecting Abeokuta as the favourable site for the lime plant.

### **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

#### **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.

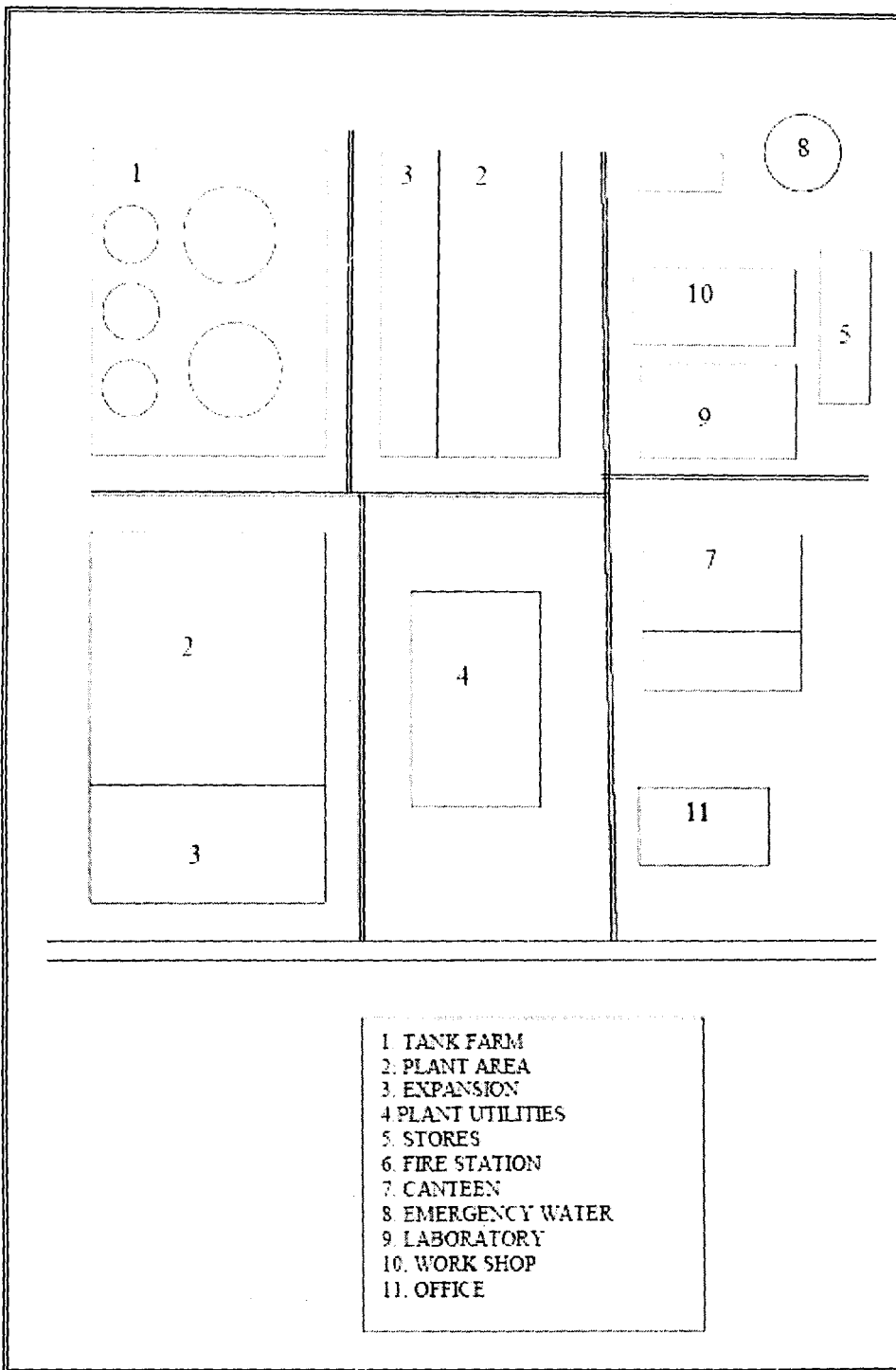


Fig. 12.1: Layout of Quicklime plant

## CHAPTER THIRTEEN

### 13.0 COSTING AND PROJECT EVALUATION

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.

(Sinnott R.K, 1999)

#### 13.1 METHOD OF COST ESTIMATION

The method of costing used in this project is **Marshall and Smith Method**.

#### 13.2 EQUIPMENT COST ESTIMATION

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 THE BIN

The cost of bin is given as

$$PC_{bin} = \frac{M_S}{280} \cdot (101.9 \cdot D^{1.066} H^{0.802} \cdot F_c)$$

where  $D$  = diameter

Cost

$H$  = height

$$F_c = F_m \cdot F_p$$

$F_p$  = factor associated with pressure

$F_m$  = factor associated with materials

and  $M_S$  = "Marshall and Smith index and has a numerical value of"  $M_S := 1100$

For the bin

$$D_{bin} = 5.954 \text{ m}$$

$$H_{bin} = 14.647 \text{ m}$$

Choosing carbon steel for the bin,

$$F_m := 1$$

$$F_p := 1$$

$$F_c := F_m \cdot F_p$$

$$F_c = 1$$

So, from

$$PC_{bin} := \frac{M\_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{D_{bin}}{m} \right)^{1.066} \left( \frac{H_{bin}}{m} \right)^{0.802} \cdot F_C \right]$$

$$PC_{bin} = 3.393 \times 10^6 \text{ Naira}$$

### 13.2.2 COST OF PRE-CRUSHER

The cost of Pre-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 numerical value of" M\_S := 1100

For the crusher,

$$D_{pre.crusher} := d_{pre.crusher} \quad d_{pre.crusher} = 1.978 \text{ m}$$

$$H_{pre.crusher} := h_{pre.crusher} \quad h_{pre.crusher} = 2.472 \text{ m}$$

Choosing carbon steel for the pre-crusher,

$$F_m := 1 \quad F_p := 1 \quad F_C := F_m \cdot F_p \quad F_C = 1$$

So, from

$$PC_{pre.} := \frac{M\_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{D_{pre.crusher}}{m} \right)^{1.066} \left( \frac{H_{pre.crusher}}{m} \right)^{0.802} \cdot F_C \right]$$

$$PC_{pre.} = 2.516 \times 10^5 \text{ Naira}$$

### 13.2.3 COST OF SCREENER 1

The cost of first screener is given as

$$PC_{screener} = \frac{M\_S}{280} \cdot \left( 101.3 \cdot A^{0.65} \cdot F_C \right)$$

where D = diameter

H = height

$$F_c = F_m \cdot F_p$$

and  $M_S = \text{"Marshall and Smith index and has a numerical value of"}$   $M_S := 1100$

For the screener 1

$$A_{\text{screener.1}} = 0.103 \text{ m}^2$$

$$F_m := 1 \quad F_p := 1 \quad F_c := F_m \cdot F_p \quad F_c = 1$$

So, from

$$PC_{\text{screner.1}} := \frac{M_S}{280} \cdot \left[ 101.3 \cdot \left( \frac{A_{\text{screener.1}}}{\text{m}^2} \right)^{0.65} \cdot F_c \right]$$

$$PC_{\text{screner.1}} = 1.335 \times 10^4 \text{ Naira}$$

### 13.2.4 COST OF CRUSHER

The cost of crusher is given as

$$PC_{\text{crusher}} = \frac{M_S}{280} \cdot \left( 101.9 \cdot D^{1.066} H^{0.802} \cdot F_c \right)$$

where D = diameter

H = height

$$F_c = F_m \cdot F_p$$

and  $M_S = \text{"Marshall and Smith index and has a numerical value of"}$   $M_S := 1100$

For the crusher,

$$D_{\text{crusher}} := d_{\text{crusher}} \quad d_{\text{crusher}} = 1.968 \text{ m}$$

$$H_{\text{crusher}} := h_{\text{crusher}} \quad h_{\text{crusher}} = 2.46 \text{ m}$$

Choosing carbon steel for the crusher,

$$F_m := 1 \quad F_p := 1 \quad F_c := F_m \cdot F_p \quad F_c = 1$$

So, from

$$PC_{\text{crusher}} := \frac{M_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{D_{\text{crusher}}}{\text{m}} \right)^{1.066} \left( \frac{H_{\text{crusher}}}{\text{m}} \right)^{0.802} \cdot F_c \right]$$

$$PC_{\text{crusher}} = 2.493 \times 10^5 \text{ Naira}$$

### 13.2.5 COST OF SCREENER 2

The cost of second screener is given as

$$PC_{\text{screener}} = \frac{M\_S}{280} \cdot (101.3 \cdot A^{0.65} \cdot F_c)$$

where D = diameter

H = height

$$F_c = F_m \cdot F_p$$

and M\_S = "Marshall and Smith index and has a numerical value of" M\_S := 1100

For the screener 1

$$A_{\text{screener.2}} = 0.1 \text{ m}^2$$

$$F_m := 1 \quad F_p := 1 \quad F_c := F_m \cdot F_p \quad F_c = 1$$

So, from

$$PC_{\text{screener.2}} := \frac{M\_S}{280} \cdot \left[ 101.3 \cdot \left( \frac{A_{\text{screener.2}}}{\text{m}^2} \right)^{0.65} \cdot F_c \right] \quad PC_{\text{screener.2}} = 1.31 \times 10^4 \text{ Naira}$$

### 13.2.6 COST OF DRYER

The cost of dryer is given as

$$PC_{\text{dryer}} = \frac{M\_S}{280} \cdot (101.3 \cdot A^{0.65} \cdot F_c)$$

where D = diameter

H = height

$$F_c = F_m \cdot F_p$$

and M\_S = "Marshall and Smith index and has a numerical value of" M\_S := 1100

For the dryer  $A_{\text{dryer}} = 2.054 \times 10^3 \text{ m}^2$   $D_{\text{dryer}} = 1.617 \text{ m}$

Choosing carbon steel for the dryer,

$$F_m := 1 \quad F_p := 1 \quad F_c := F_m \cdot F_p \quad F_c = 1$$

So, from

$$PC_{\text{dryer}} := \frac{M\_S}{280} \cdot \left[ 101.3 \cdot \left( \frac{A_{\text{dryer}}}{m^2} \right)^{0.65} \cdot F_c \right]$$

$$PC_{\text{dryer}} = 8.324 \times 10^6 \text{ Naira}$$

### 13.2.5 COST OF FLUIDIZED BED DECARBONIZATION FURNACE

The cost of fluidized bed decarbonization furnace is given as

$$PC_{\text{furnace}} = \frac{M\_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{D_{\text{furnace}}}{m} \right)^{1.066} \left( \frac{H_{\text{furnace}}}{m} \right)^{0.802} \cdot F_c \right]$$

where

$$F_c = F_m \cdot F_p$$

and  $M\_S =$  "Marshall and Smith index and has a numerical value of"  $M\_S := 1100$

For the furnace

$$D_{\text{furnace}} = 1.824 \text{ m} \quad H_{\text{furnace}} = 4.56 \text{ m}$$

Choosing stainless steel for the furnace,

$$F_m := 3.67 \quad F_p := 1.15 \quad F_c := F_m \cdot F_p \quad F_c = 4.22$$

So, from

$$PC_{\text{furnace}} := \frac{M\_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{D_{\text{furnace}}}{m} \right)^{1.066} \left( \frac{H_{\text{furnace}}}{m} \right)^{0.802} \cdot F_c \right]$$

$$PC_{\text{furnace}} = 1.592 \times 10^6 \text{ Naira}$$

### 13.2.4 COST OF CYCLONE

The cost of crusher is given as

$$PC_{\text{cyclone}} = \frac{M\_S}{280} \cdot \left( 101.9 \cdot D^{1.066} H^{0.802} \cdot F_c \right)$$

where  $D =$  diameter

$H =$  height

$$F_c = F_m \cdot F_p$$

and  $M\_S =$  "Marshall and Smith index and has a numerical value of"  $M\_S := 1100$

For the cyclone,  $d_{\text{cyclone}} = 0.95 \text{ m}$   $h_{\text{cyclone}} = 3.8 \text{ m}$



Choosing carbon steel for the crusher,

$$F_m := 1 \quad F_p := 1$$

$$F_c := F_m \cdot F_p \quad F_c = 1$$

So, from

$$PC_{cyclone} := \frac{M_S}{280} \cdot \left[ 101.9 \cdot \left( \frac{d_{cyclone}}{m} \right)^{1.066} \left( \frac{h_{cyclone}}{m} \right)^{0.802} \cdot F_c \right] \cdot 3$$

$$PC_{cyclone} = 4.876 \times 10^5 \text{ Naira}$$

### 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 numerical value of"  $M_S := 1100$

For the cooler

$$A_{cooler} = 169.982 \text{ m}^2$$

Choosing stainless steel for the cooler,

$$F_m := 3.67 \quad F_p := 1.15 \quad F_c := F_m \cdot F_p \quad F_c = 4.22$$

So, from

$$PC_{cooler} := \frac{M_S}{280} \cdot \left[ 101.3 \cdot \left( \frac{A_{cooler}}{\text{m}^2} \right)^{0.65} \cdot F_c \right]$$

$$PC_{cooler} = 6.955 \times 10^6 \text{ Naira}$$

### Total Purchase Cost of Equipments

The total purchased cost of equipments is, calculated as the sum of individual cost of purchase of

$$C_T := (PC_{bin} + PC_{dryer} + PC_{crusher} + PC_{scner.1} + PC_{furnace} + PC_{cooler} + PC_{scner.2} + PC_{pre.} + PC_{cyclone})$$

$$PC_T = 2.128 \times 10^7 \text{ Naira}$$

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

$$FC_{\text{initial}} := PC_T$$

$$FC_{\text{initial}} = 2.128 \times 10^7 \text{ Naira}$$

## 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

$$\text{Assuming } PEC := 37\% \cdot FC_{\text{initial}} \qquad PEC = 7.873 \times 10^6 \text{ Naira}$$

#### 2. Installation, including insulation and painting, 25-55% of purchased equipment cost

$$\text{Assume } \text{Installation} := 55\% \cdot PEC \qquad \text{Installation} = 4.33 \times 10^6 \text{ Naira}$$

#### 3. Instrumentation and controls, installed, 6-30% of purchased equipment cost

Assuming

$$\text{Instrumentation} := 35\% \cdot PEC \qquad \text{Instrumentation} = 2.756 \times 10^6 \text{ Naira}$$

#### 4. Piping installed, 10-80% of purchased equipment cost

Assuming

$$\text{Piping} := 70\% \cdot PEC \qquad \text{Piping} = 5.511 \times 10^6 \text{ Naira}$$

#### 5. Electrical, installed, 10-40% of purchased equipment cost

Assuming

$$\text{Electrical} := 35\% \cdot PEC \qquad \text{Electrical} = 2.756 \times 10^6 \text{ Naira}$$

So, the cost of equipment, installation, instrumentation, piping, electrical, insulation and

painting is given as

$$CA := PEC + \text{Installation} + \text{Instrumentation} + \text{Piping} + \text{Electrical} \qquad CA = 2.323 \times 10^7 \text{ Naira}$$

#### B. Buildings, process and auxiliary, 10-70% of purchased equipment cost

Assuming

$$\text{Buildings} := 70\% \cdot PEC \qquad \text{Buildings} = 5.511 \times 10^6 \text{ Naira}$$

**C. Service facilities and yard improvements, 40-100% of purchased equipment cost**

Assuming

$$\text{Service} := 70\% \cdot \text{PEC}$$

$$\text{Service} = 5.511 \times 10^6 \text{ Naira}$$

**D. Land, 1-2% of fixed capital investment or 5-15% of purchased equipment cost)**

Assuming

$$\text{Land} := 15\% \cdot \text{PEC}$$

$$\text{Land} = 1.181 \times 10^6 \text{ Naira}$$

Thus, the direct cost is equal to

$$\text{Direct\_Cost} := \text{CA} + \text{Buildings} + \text{Service} + \text{Land}$$

$$\text{Direct\_Cost} = 3.543 \times 10^7 \text{ Naira}$$

**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

$$\text{Engineering} := 30\% \cdot \text{Direct\_Cost}$$

$$\text{Engineering} = 1.063 \times 10^7 \text{ Naira}$$

**B. Construction expense and contractor's fee, 10-60% of direct cost**

Assuming

$$\text{Construction} := 55\% \cdot \text{Direct\_Cost}$$

$$\text{Construction} = 1.949 \times 10^7 \text{ Naira}$$

**C. Contingency, 15-55% of direct cost**

Assuming

$$\text{Contingency} := 40\% \cdot \text{Direct\_Cost}$$

$$\text{Contingency} = 1.417 \times 10^7 \text{ Naira}$$

Thus, indirect cost is equal to

$$\text{Indirect\_Cost} := \text{Engineering} + \text{Construction} + \text{Contingency}$$

$$\text{Indirect\_Cost} = 4.429 \times 10^7 \text{ Naira}$$

**III. Fixed Capital Investment:**

Fixed capital investment is taken as Direct cost + Indirect cost

$$\text{Fixed\_Capital} := \text{Direct\_Cost} + \text{Indirect\_Cost}$$

$$\text{Fixed\_Capital} = 7.972 \times 10^7 \text{ Naira}$$

**IV. Working Capital, 11-50% of fixed capital investment**

Assuming

$$\text{Working\_Capital} := 50\% \cdot \text{Fixed\_Capital}$$

$$\text{Working\_Capital} = 3.986 \times 10^7 \text{ Naira}$$

**V. Total Capital Investment (TCI):**

Total capital investment is taken as Fixed capital investment + Working capital

Assuming  $Total\_CI := Fixed\_Capital + Working\_Capital$

$$Total\_CI = 5.979 \times 10^9 \text{ Naira}$$

### 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 equipment and 2-3% of building value for

buildings  
Assuming

$$Depreciation := 13\% \cdot Fixed\_Capital + 3\% \cdot Buildings \quad Depreciation = 1.053 \times 10^7 \text{ Naira}$$

**ii. Local Taxes**, 1-4% of fixed capital investment

Assuming

$$Tax := 3\% \cdot Fixed\_Capital \quad Tax = 2.391 \times 10^6 \text{ Naira}$$

**iii. Insurance**, 0.4-1% of fixed capital investment)

Assuming

$$Insurance := 0.75\% \cdot Fixed\_Capital \quad Insurance = 5.979 \times 10^5 \text{ Naira}$$

**iv. Rent**, 8-12% of value of fixed capital investment

Assuming

$$Rent := 10\% \cdot Fixed\_Capital \quad Rent = 7.972 \times 10^6 \text{ Naira}$$

Thus, fixed charges is given as

$$Fixed\_charge := Depreciation + Tax + Insurance + Rent \quad Fixed\_charge = 2.149 \times 10^7 \text{ Naira}$$

Assuming

$$Fixed\_Capital = 15\% \cdot TPC$$

making total product cost, TPC, the subject of the formula,

$$TPC = \frac{FC}{15\%} \quad TPC := \frac{Fixed\_charge}{15\%} \quad TPC = 1.433 \times 10^8 \text{ Naira}$$

## B. Direct Production Cost:

### i. Raw materials, 10-50% of total product cost)

Assuming

$$\text{Raw\_mat} := 49\% \cdot \text{TPC}$$

$$\text{Raw\_mat} = 7.02 \times 10^7 \text{ Naira}$$

### ii. Operating Labour (OL), 10-20% of total product cost

Assuming

$$\text{Operating}_{\text{lab}} := 16\% \cdot \text{TPC}$$

$$\text{Operating}_{\text{lab}} = 2.292 \times 10^7 \text{ Naira}$$

### iii. Direct Supervisory and Clerical Labour (DS & CL), 10-25% of OL

Assuming

$$\text{Direct}_{\text{superv}} := 20\% \cdot \text{Operating}_{\text{lab}}$$

$$\text{Direct}_{\text{superv}} = 4.584 \times 10^6 \text{ Naira}$$

### iv. Utilities, 10-20% of total product cost

Assuming

$$\text{Utility} := 18\% \cdot \text{TPC}$$

$$\text{Utility} = 2.579 \times 10^7 \text{ Naira}$$

### v. Maintenance and repairs (M & R), 2-10% of fixed capital investment

Assuming

$$\text{Mainten} := 7\% \cdot \text{Fixed\_Capital}$$

$$\text{Mainten} = 5.58 \times 10^6 \text{ Naira}$$

### vi. Operating Supplies, 10-50% of M & R or 0.5-1% of FCI

Assuming

$$\text{Operating}_{\text{sply}} := 50\% \cdot \text{Mainten}$$

$$\text{Operating}_{\text{sply}} = 2.79 \times 10^6 \text{ Naira}$$

### vii. Laboratory Charges, 10-20% of OL

Assuming

$$\text{Lab}_{\text{charges}} := 18\% \cdot \text{Operating}_{\text{lab}}$$

$$\text{Lab}_{\text{charges}} = 4.126 \times 10^6 \text{ Naira}$$

### viii. Patent and Royalties, 0-6% of total product cost

Assuming

$$\text{Patent} := 6\% \cdot \text{TPC}$$

$$\text{Patent} = 8.596 \times 10^6 \text{ Naira}$$

Thus, direct production cost is

$$\text{DPC} := \text{Raw\_mat} + \text{Operating}_{\text{lab}} + \text{Direct}_{\text{superv}} + \text{Utility} + \text{Mainten} + \text{Operating}_{\text{sply}} + \text{Lab}_{\text{charges}} + \text{Patent}$$

$$\text{DPC} = 1.446 \times 10^8 \text{ Naira}$$

**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,

Considering the plant overhead cost to be 55% of OL, DS & CL and M & R laboratories, and storage facilities.

Therefore,

$$\text{Plant} := 55\% \cdot (\text{Operating}_{\text{lab}} + \text{Direct}_{\text{superv}} + \text{Mainten})$$

$$\text{Plant} = 1.82 \times 10^7 \text{ Naira}$$

Manufacture cost = Direct production cost + Fixed charges + Plant overhead cost

$$\text{Manuf}_{\text{cost}} := \text{DPC} + \text{Fixed}_{\text{charge}} + \text{Plant}$$

$$\text{Manuf}_{\text{cost}} = 1.843 \times 10^8 \text{ Naira}$$

**II. General Expenses = Administrative costs + distribution and selling costs + research**

and development costs

**A. Administrative costs, 2-6% of total product cost**

Assuming

$$\text{Admin} := 4.5\% \cdot \text{TPC}$$

$$\text{Admin} = 6.447 \times 10^6 \text{ Naira}$$

**B. Distribution and Selling Costs, 2-20% of total product cost; includes costs for sales offices, salesmen, shipping, and advertising.**

Assuming

$$\text{Distr} := 17\% \cdot \text{TPC}$$

$$\text{Distr} = 2.435 \times 10^7 \text{ Naira}$$

**C. Research and Development Costs, about 3% of total product cost**

Assuming

$$\text{Resea} := 3\% \cdot \text{TPC}$$

$$\text{Resea} = 4.298 \times 10^6 \text{ Naira}$$

Thus, general expenses,

$$\text{Gener} := \text{Admin} + \text{Distr} + \text{Resea}$$

$$\text{Gener} = 3.51 \times 10^7 \text{ Naira}$$

**IV. Total Production Cost = Manufacture Cost + General Expenses**

$$\text{TProdC} := \text{Manuf}_{\text{cost}} + \text{Gener}$$

$$\text{TProdC} = 2.194 \times 10^8 \text{ Naira}$$

## V. Gross Earnings/Income:

The selling price of Quicklime is equal to

$$\text{Selling\_price} := 32.5 \cdot \frac{\text{Naira}}{\text{kg}}$$

$$\text{Quantity\_produced} := 10160.47 \cdot \frac{\text{kg}}{\text{hr}}$$

$$\text{Quantity\_produced} = 8.906 \times 10^7 \frac{\text{kg}}{\text{yr}}$$

Assuming that the attainment is: Attainment := 331 · day

Total income = Selling price x quantity of product manufactured

$$\text{Total\_income} := \text{Selling\_price} \cdot \text{Quantity\_produced} \cdot \text{Attainment}$$

$$\text{Total\_income} = 2.623 \times 10^9 \text{ Naira}$$

Gross income = Total income - Total Product Cost

That is, Gross\_income := Total\_income - TProdC

$$\text{Gross\_income} = 2.404 \times 10^9 \text{ Naira}$$

Assuming the tax rate to be 25% (common), Tax\_rate := 25%

Net profit = Gross income - Taxes

$$\text{Taxes} := \text{Tax\_rate} \cdot \text{Gross\_income}$$

$$\text{Taxes} = 6.01 \times 10^8 \text{ Naira}$$

$$\text{Net\_profit} := \text{Gross\_income} - \text{Taxes}$$

$$\text{Net\_profit} = 1.803 \times 10^9 \text{ Naira}$$

### Rate of Return:

$$\text{Rate\_of\_return} = \frac{\text{Net\_profit}}{\text{Total\_CI}} \cdot 100\%$$

Therefore,

$$\text{ROR} := \frac{\text{Net\_profit}}{\text{Total\_CI}} \cdot 100\%$$

$$\text{ROR} = 30.155 \%$$

### Pay-Back Period:

The pay-back period is calculated as the reciprocal of the rate of return.

Therefore,

$$\text{PBP} := \frac{1}{\text{ROR}} \cdot \text{yr}$$

$$\text{PBP} = 3.316 \text{ yr}$$

which is approximately equal to

$$\text{PBP} = 3 \text{ yr}$$

## Cash Flow

Cash flow is the difference between the amount earned and the amount expended.

$$\text{Cash\_Flow} := \text{Total\_income} - \text{TProdC}$$

$$\text{Cash\_Flow} = 2.404 \times 10^9 \text{ Naira}$$

## Net Present Worth of the Project

The net present worth (NPW) of cash flow in year n is given as

$$\text{NPW} = \sum_{i=1}^n \frac{\text{Cash\_Flow}}{(1+r)^i} \quad r := \text{ROR} \quad n := 1$$

Therefore,

$$\text{NPW} := \sum_{i=1}^n \frac{\text{Cash\_Flow}}{(1+r)^i} \quad \text{NPW} = 1.847 \times 10^9 \text{ Naira}$$

## Discounted Cash Flow Rate of Return

The discounted cash flow is the interest rate that will make the condition given as

$$\text{DCF} = \sum_{i=1}^n \frac{\text{Cash\_Flow}}{(1+r)^i} = 0$$

Using trial-and-error calculations as suggested by Sinnott R. K. (Coulson and Richardson's

Chemical Engineering, 3rd Edition, pg 277,

$$r := 45 \cdot \%$$

$$n := 65$$

$$\text{DCFRR} := r$$

$$\text{DCF} := \sum_{i=1}^n \frac{\text{Cash\_Flow}}{(1+r)^i} \quad \text{DCF} = 0$$

Therefore, the Discounted Cash Flow Rate of Return (DCFRR) is equal to  $\text{DCFRR} = 45\%$ .

## Return on Investment

This is calculated as given thus.

Return on investment (ROI) is given by the expression,

$$\text{ROI} = \frac{\text{Total\_profit\_less\_depreciation}}{\text{Total\_investment}}$$

That is,

$$\text{ROI} := \frac{\text{Total\_income} - \text{Depreciation}}{\text{Total\_income}} \cdot 100\% \quad \text{ROI} = 99.599\%$$



## Project Income and Expenses Statement for 2006-2009

This plant was designed to produce 10 tonnes per hr (Basis :=  $10 \cdot \frac{\text{tonne}}{\text{hr}}$ ) of lime. Making the plant attainment to be Attainment = 331 day, the plant is thus required to produce

$$\text{Basis} \cdot \text{Attainment} = 7.944 \times 10^4 \text{ tonne}$$

It is expected that the performance of the plant should increase every year. For instance,

assuming that the plant operates at 90% capacity in the first year, 95% capacity in the second

year, 99% 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 2006 to 2009

DESCRIPTION	YEARS			
	2006	2007	2008	2009
Tonnes/hr	10.00	10.56	11.00	11.11
Capacity (%)	90	95	99	100
<b>REVENUE</b>	<b>Amount in Naira</b>			
Net sales	2623000000	2768722222	2885300000	2914444444
<b>EXPENDITURE</b>				
Raw material	70200000	74100000	77220000	78000000
Factory labour	22920000	24193333.33	25212000	25466666.67
Depreciation	10530000	11115000	11583000	11700000
Overhead	18200000	19211111.11	20020000	20222222.22
<b>TOTAL</b>	<b>121850000</b>	<b>128619444.4</b>	<b>134035000</b>	<b>135388888.9</b>
<b>PROFIT</b>				
Before tax	2404000000	2537555556	2644400000	2671111111
Tax	601000000	634388888.9	661100000	667777777.8
<b>Net profit</b>	<b>1803000000</b>	<b>1903166667</b>	<b>1983300000</b>	<b>2003333333</b>

### Conclusion on the Economic Viability of the Project

The total production cost of the plant which is  $T_{\text{ProdC}} = 2.194 \times 10^8$  Naira and a net profit of  $\text{Net\_profit} = 1.803 \times 10^9$  Naira have revealed that the project is economically viable with a pay back period of approximately  $\text{PBP} = 3$  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. The safety of workers, equipments and infrastructures should be highly evaluated during the design implementation stage of the design.

ii. The recycle design should be considered without further delay, since it is useful in reducing the level of lime plant effluent, and it also reduces costs.

iii. Adequate data and technological parameters should be at the possession of the lime plant operations at all time to forestall any unwanted accident.

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.

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.

Procurement of raw materials and equipments should be based on strict regulation of specification and maximum quality.

Lime plant should not be operated above the design specification to avoid abnormal conditions and explosions.

The implementation of this design work must be adequately supervised by the experts.

The lime plant should be sited close to the source of raw materials.

Alternative sources of energy should be available at all times to avoid lime plant failure and possible sources of failure.

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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