



Report of Cooperative Education

Preliminary Equipment Design for Fertilizer Plant



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King Mongkut's Institute of Technology Ladkrabang
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Co-operative Title: Preliminary Equipment Design for Fertilizer Plant
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Abstract

This project is a preliminary equipment design for fertilizer plant dealing with phosphoric acid and ammonium phosphate processes. The main equipment in this study are rotary dryer, cyclone and packed bed scrubber. Four calculation data sheets, i.e., calculations of mass balances, rotary dryer, cyclone and packed bed scrubber are made to verify the vendor data sheets. Mass balances are developed to design the rotary dryer, cyclone and packed bed scrubber. Heat duty of the rotary dryer is calculated from heat capacities and temperature of the relevant substances. Cyclone geometry is based on fixed configuration model. Pressure drop in the cyclone involves with particle acceleration, barrel friction, gas flow reversal and exit contraction. The flow rate of water in packed bed scrubber is determined by the equilibrium line which is estimated by Henry's law. Column diameter of packed bed scrubber is calculated by mass flux in generalized flooding and pressure drop correlation graph. Packing height is based on number of transfer units and overall transfer units.

Heat duty of the rotary dryer is 12.12 MW. Cyclone diameter and height are 2.21 and 6.63 m, respectively. Packed bed scrubber uses 452 m³/h of liquid water to absorb ammonia gas. The column diameter and packing height are 5.38 and 3.39 m, respectively. All of the calculations are compared with the vendor data sheets. Each calculation result is less than 11 percent deviation. The calculation data sheets can be used for preliminary equipment design in acceptable ranges.

Keywords: Fertilizer, Dryer, Cyclone, Scrubber

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NOMENCLATURE

A	= Area (m^2)
D	= Column Diameter (m)
d_{in}	= Inlet Diameter (m)
d_p	= Particle Diameter (mm)
d_{pc}	= Cutting Particle Size (μm)
e	= Pipe Roughness
E	= Vapor Rressure (Pa)
Ed	= Vapor Pressure Difference (Pa)
Eg	= Calculation Vapor Pressure (Pa)
Es	= Saturation Vapor Pressure (Pa)
f	= Friction Factor
F	= Packing Factor (m^{-1})
g_c	= Gravitational Constant (m/s^2)
G	= Mass Flow Rate of Inlet Gas Stream (mol/h)
G'	= Mass Flux ($g/s \cdot m^2$)
K	= Constant Value from Graph
L	= Mass Flow Rate of Inlet Liquid Stream (mol/h)
L'	= Liquid Molar Flow Rate (mol/h)
N_s	= Turn Numbers
P_{sta}	= Actual Station Pressure (kPa)
Re	= Reynolds Number
Rh	= Relative Humidity
T	= Temperature ($^{\circ}C$)
T_w	= Wet Bulb Temperature ($^{\circ}C$)
v_i	= Air Velocity (m/s)
v_{in}	= Gas Velocity (m/s)
v_{vessel}	= Velocity in Vessel (m/s)
V'	= Gas Molar Flow Rate (mol/h)
W	= Inlet Width (m)

NOMENCLATURE (Cont.)

X_0	= Mole Fraction of Solute in Inlet Liquid
X_1	= Mole Fraction of Solute in Outlet Liquid
Y_1	= Mole Fraction of Solute in Inlet Gas
Y_2	= Mole Fraction of Solute in Outlet Gas
μ	= Viscosity (kg/m•s)
μ_l	= Liquid Viscosity (Pa•s)
ρ_p	= Solid Particle Density (kg/m ³)
ρ_g	= Gas Density (kg/m ³)
ρ_l	= Liquid Density (kg/m ³)
η	= Collection Efficiency
\emptyset	= Ratio of Specific Gravity of the Scrubber Liquid to that of Water
ΔP	= Total Pressure Drop (Pa)
ΔP_i	= Pressure Drop of Inlet Contraction (Pa)
ΔP_p	= Pressure Drop of Particle Acceleration (Pa)
ΔP_b	= Pressure Drop of Barrel Friction (Pa)
ΔP_g	= Pressure Drop of Gas Flow Reversal (Pa)
ΔP_e	= Pressure Drop of Exit Contraction (Pa)

CHAPTER I

INTRODUCTION

1.1 Background

TTCL Public Company Limited (TTCL) is the integrated EPC (Engineering, Procurement and Construction) company in Thailand. TTCL has experiences and expertise in providing integrated design and engineering, procurement of machinery and equipment, and construction (Integrated EPC) of turnkey projects for industrial and process plants, mainly in energy, petrochemical, chemical and power industries.

Fertilizer is a one of project to produce nitrogen, phosphorous and potassium compounds. Location of plants in the past are Bangladesh, Vietnam and Thailand. Although several plants were completely constructed with different licensors. This project is studying about fertilizer plant at Turkmenistan in proposal step. Details of each unit must be clarified before construction or tender.

Fertilizer is produced from phosphate, ammonium and potassium that are mixed with different components for each formula. The process for manufacturing ammonium phosphate (AP) is relatively simple. In a common method, ammonia (NH_3) and phosphoric acid (H_3PO_4) are reacted and the resulting slurry of AP is solidified in a granulator. Target plant capacity of the design project is 1,000 tons/day.

This project focus on design of fertilizer production by comparing data with conventional plant. Firstly, Mass balance is rechecked to confirm the flow rate that use for calculation each unit. The equipment that are calculated to verify with vendor's data sheet are rotary dryer, cyclone and packed bed scrubber. In proposal step the owner or licensor data must be clarified to use normal condition and margin for design capacity and sizing of equipment. Rotary dryer uses for moisture reduction. The product must be less than 2 wt% moisture that contain of 5 wt% of nitrogen and 39 wt% of phosphorous pentoxide. Cyclone uses to collect dust concentration. The law fixes dust concentration that is released to atmosphere. Packed bed scrubber used to adsorb ammonia gas that vaporize because its boiling point is lower than ambient temperature. All of results are compared with vendor's outcome¹

1.2 Objectives

Preliminary equipment design in this project are dryer, cyclone and scrubber

1.3 Scopes of Work

1.3.1 Studying about the principles of fertilizer plant

1.3.2 Studying about the process flow diagrams (PFDs) of phosphoric acid and ammonium phosphate processes

1.3.3 Creating calculation templates of rotary dryer, cyclone and packed bed scrubber

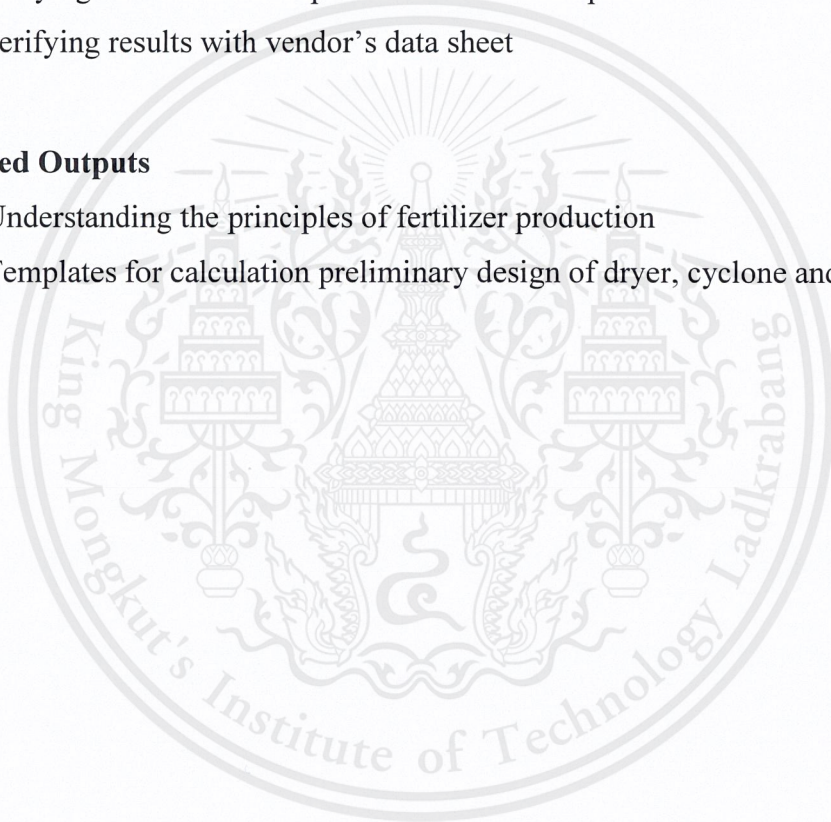
1.3.4 Studying about solid transportation in fertilizer plant

1.3.5 Verifying results with vendor's data sheet

1.4 Expected Outputs

1.4.1 Understanding the principles of fertilizer production

1.4.2 Templates for calculation preliminary design of dryer, cyclone and scrubber



CHAPTER II

LITERATURE REVIEW

This project is studying about the ammonium phosphate fertilizer plant that includes two processes: phosphoric acid and ammonium phosphate processes. Reactor, filter, evaporator, granulator, dryer and screen are main equipment. Preliminary equipment design templates in fertilizer plant are created such as rotary dryer, cyclone and venturi scrubber. Phosphoric acid production is produced with phosphate rock that is mainly used for fertilizer production. The process of phosphoric acid used for fertilizer industrial has been produced by two methods: thermal method and wet method. In addition almost all phosphoric acid is produced by wet method. Moreover ammonium phosphate is produced by phosphoric acid phosphate rock and sulfuric acid that reacted to produce tri super phosphate and single super phosphate. Slurry from reactor is solidified in granulator with additional ammonia feed. Fertilizer product is composed 39% of P_2O_5 and 5% of N.

2.1 Fertilizer (Nyers, J. M. et al., 1979)

Fertilizer is a material that are basic chemical elements for development and growth of plants. The main chemical elements for plant growth are carbon, hydrogen and oxygen in air and water. Moreover nitrogen, phosphorous and potassium in soil are adding by fertilizer. Classifications of them are single fertilizer and mixture fertilizer that are essential in today's agricultural system to replace the element extracted from the soil in from of food and agricultural products.

2.1.1 Plant Nutrients

Nine Plant nutrients are required in relative large amount and major elements (carbon, hydrogen and oxygen) are obtained from carbon dioxide in atmosphere and water. Moreover primary, secondary and macronutrients that make up to 5-10% of dry matter. Many countries express quantities in term of element nitrogen, phosphorus pentoxide and potassium oxide and others nutrient usually are express on an element basis.

2.1.2 Fertilizer Grade

Grade is customary to refer to a given fertilizer product by a series number separated by dashes. Each of the number indicates the amount of nutrient that guarantees fertilizer product by manufacture. First, second and third number expresses the weight in kilogram of nitrogen, phosphorus pentoxide and potassium oxide respectively per 100 kilogram of fertilizer product. The elements basis is shown in Table 2.1 for convert by using the factors.

Example of Fertilizer Grade

A fertilizer product with a grade 18-46-0 has a following content

18% N or 18 kg N in every 100 kg

46% P₂O₅ or 46 kg P₂O₅ in every 100 kg

0% K₂O or no K₂O

Table 2.1 Conversion Factor of Plant Nutrients (Nyers, J. M. et al., 1979)

Oxide forms		Factors		Element
P ₂ O ₅	X	0.44	=	P
K ₂ O	X	0.83	=	K
CaO	X	0.71	=	Ca
MgO	X	0.60	=	Mg
SO ₃	X	0.40	=	S

2.1.3 Fertilizer Specification

The rapid increase in the world's population is the main driving force for the growing demand for agricultural products for nutrients support plant growth. Fertilizer specifications are normally used in the contract between the buyer and seller to ensure the agreement on product characteristics or more often to define the product. A well fertilizer specification should include the following elements detail

- 1) Nutrient Contents and Concentrations.
- 2) Nutrient Chemical Composition.
- 3) Moisture Content.
- 4) Particle Size Distribution.

- 5) Physical Condition.
- 6) Solubility or Availability.
- 7) Conditioner
- 8) Special Limitation Pertaining to Phototoxic Production Byproducts or Additives.
- 9) Packaging Details.
- 10) Methodology Used In Quantifying or Qualifying Items.
- 11) Penalties or Discounts for Deviation from the Stated Values and Condition.

From buyer's standpoint, one might consider that the more detailed the specification, the more certain the buyer becomes of the product quality. It is important then to state in the specifications not only what is wanted in the product but also what is unwanted in the product.

2.2 Process Description (Rawlings, G. D. and Reznik, R. B. 2000, European fertilizer manufacturers association, 2000)

2.2.1 Phosphoric Acid Process

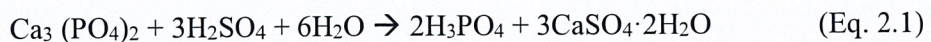
Phosphoric acid can be made by one of two processes: a wet process or a thermal process. Each of these processes produces a very different grades of phosphoric acid. Acid produced via the wet process is typically referred to as merchant-grade phosphoric acid. During the wet process, phosphate rock is reacted with sulfuric acid to produce an acid product containing 40 to 54 percent phosphoric acid (P_2O_5) and a calcium sulfate byproduct, gypsum. In Europe, three types of phosphoric acid process, according to the condition of calcium sulphate produced, are anhydrite, hemihydrate and dihydrate. Different processes are needed because phosphate rock and gypsum byproduct. Phosphate rocks have several grade as shown in Table 2.2. Moreover thermal process phosphoric acid is higher purity and is used in the manufacture of high grade chemicals such as pharmaceuticals, detergents, food products, beverages, and other non-fertilizer products.

Table 2.2 Variation in Chemical Analysis of Various Phosphate Rocks (Nyers, J. M. et al., 1979)

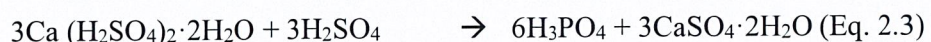
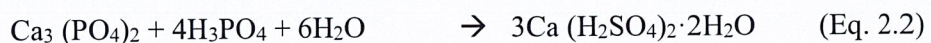
	CEI Russia*	S.AFRICA Phalaborwa*	MOROCCO Khouribga	USA Florida	SENEGAL	TOGO
P ₂ O ₅	38.9	36.8	33.4	34.3	36.7	36.7
CaO	50.5	52.1	50.6	49.8	50.0	51.2
SiO ₂	1.1	2.6	1.9	3.7	5.0	4.5
F	3.3	2.2	4.0	3.9	3.7	3.8
CO ₂	0.2	3.5	4.5	3.1	1.8	1.6
Al ₂ O ₃	0.4	0.2	0.4	1.1	1.1	1.0
Fe ₂ O ₃	0.3	0.3	0.2	1.1	0.9	1.0
MgO	0.1	1.1	0.3	0.3	0.1	0.1
Na ₂ O	0.4	0.1	0.7	0.5	0.3	0.2
K ₂ O	0.5	0.1	0.1	0.1	0.1	0.1
Organics	-	0.1	0.3	0.5	-	-
Organ. C	0.1	-	-	0.2	0.4	0.1
SO ₃	0.1	0.2	1.6	0.1	-	0.3
Cl	-	-	0.1	-	-	0.1
SrO	2.9	0.2	0.1	-	-	-

Note: *Igneous

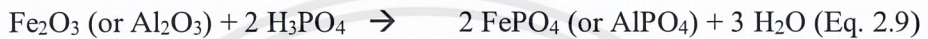
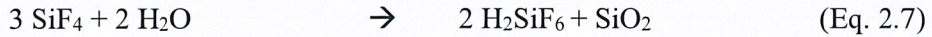
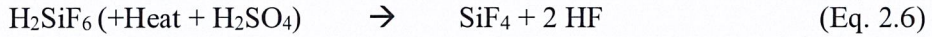
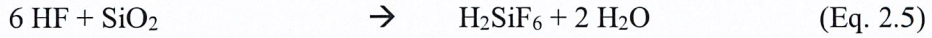
In wet method, phosphate rock that consist of 24.5% P₂O₅ is reacted with sulfuric acid in reactor. Reactor has two parts: attack (4 compartments) and digestion (2 compartments). Phosphate rock and sulfuric acid are added in first and second compartments of attack part. Reaction occur and circulate in four compartments of attack. This reaction is exothermic reaction.



This reaction takes place in two steps:



In addition the most important of minor reaction occur as the following.



The sulphate concentration in attack system is normally be maintained at about 2% excess SO_3 . Flash cooler is needed for removing heat by liquid in fourth compartment and slurry of gypsum and phosphoric acid are overflow to digestion part. P_2O_5 losses will occur in two types of extraction losses. The first reason is unreacted phosphate rock from insufficient grinding of the phosphate rock with the sulfuric acid. The second extraction loss is the co-crystallized P_2O_5 due to formation of a solid solution of calcium phosphate in the gypsum.

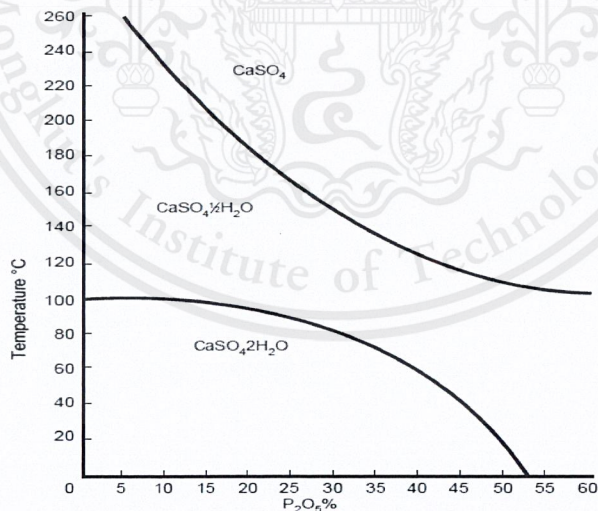


Figure 2.1 Dependence of Calcium Sulphate Hydrate Crystallization on Temperature and P_2O_5 (Nyers, J. M. et al., 1979)

High concentration of acid is produced if byproduct is dihydrate that is easiest to separate. Calcium sulphate exists in a number of different crystal forms depending particularly on the prevailing conditions of temperature, P₂O₅ concentration and free sulphate content (see Figure 2.1). Condition in reactor is controlled temperature between 75- 80 °C. Slurry from reactor is separated in tilting pan filter with vacuum system. Filter cake is washed with water after removed acid. Some of acid that has high solid particle suspension is recycled to reactor. Weak acid is send to weak acid storage tank and gypsum is discharged. Evaporator is used to increase acid concentration by heat from low pressure steam. The condensate is discharged by gravity through a self-draining line to the condensate receiver. Weak acid is recirculated in evaporator until acid concentration is about 42% P₂O₅. Concentrated phosphoric acid is transferred to storage tank.

2.2.2 Ammonium Phosphate Process

Ammonium phosphate (NH₄H₂PO₄) is produced by reacting phosphoric acid (H₃PO₄) with anhydrous ammonia (NH₃). Ammoniated superphosphates are produced by adding normal superphosphate or triple superphosphate that is reacted from phosphate rock with sulfuric acid and phosphoric acid to the mixture. The reaction of them are following:

Tri Superphosphate (TSP)



Single superphosphate (SSP)



Den unit is required for solidification and crystallization of slurry (mono calcium phosphate) from reactor by using time around 30 minutes. Granulator are used to mix slurry and additional phosphate rock, ammonia and mixture of phosphoric acid and ammonia for specification of fertilizer. Phosphoric acid is mixed in an acid surge tank with 93 percent sulfuric acid (H₂SO₄) which is used for product analysis control, and with recycled acid from wet scrubbers. Mixed acids are then partially neutralized with liquid or gaseous anhydrous ammonia in a brick-lined acid reactor. All of the phosphoric acid and approximately 70 percent of the ammonia are introduced into this vessel. Slurry of ammonium phosphate and 22 percent water

are produced and sent through steam-traced lines to the ammoniator-granulator. Slurry from the reactor is distributed on the bed; the remaining ammonia (approximately 30 percent) is spared underneath. Granulation, by agglomeration and by coating particulate with slurry, takes place in the rotating drum and is completed in the dryer. Ammonia-rich off gases pass through a wet scrubber before exhausting to the atmosphere. Primary scrubbers use raw materials mixed with acid (such as scrubbing liquor), and secondary scrubbers use pond water.

Moist ammonium phosphate granules are transferred to a rotary co-current dryer and then to a cooler. Before being exhausted to the atmosphere, these off gases pass through cyclones and wet scrubbers. Cooled granules pass to a double-deck screen, in which oversize and undersize particles are separated from product particles. The product ranges in granule size from 2 to 4 millimeters. The oversized granules are crushed, mixed with the undersized, and recycled back to the ammoniator granulator.

The fertilizer grade of diammonium phosphate is 18-46-0 that shown in Table 2.3. Product of this plant include 5% nitrogen and 39% phosphorus. One of the major cropping fertilizers used as a source of phosphorus and nitrogen, MAP and MAP blends are used extensively in cropping systems and for sowing pastures. The low level of nitrogen makes it useful as a 'starter' fertilizer and as there is no free ammonia, the risk of affecting germinating seeds is minimal.

Table 2.3 Common Basic Fertilizer Materials Used for Blending and their Nutrient Contents

[Maguire, R., 2009]

Material	Analysis	N (%)	P ₂ O ₅ (%)	K ₂ O (%)
Ammonium nitrate	33-0-0	33	0	0
Ammonium sulfate*	21-0-0-24S	21	0	0
Diammonium phosphate	18-46-0	18	46	0
Potassium chloride (muriate of potash)	0-0-60	0	0	60
Potassium sulfate**	0-0-50-16S	0	0	50
Potassium magnesium sulfate***	0-0-22-23S-11Mg	0	0	22
Triple super phosphate	0-46-0	0	46	0
Urea	46-0-0	46	0	0

Note: * Ammonium sulfate contains 24% sulfur (S)

** Potassium sulfate contains 16% S

*** Potassium magnesium sulfate contains 23% S and 11% magnesium (Mg)

2.3 Filter (Zverev, A. I. 1967, Huelsman, L. P., and Allen, P. E., 1980)

Filtration is the separation of a fluid-solids mixture involving passage of most of the fluid through a porous barrier which retains most of the solid particulates contained in the mixture. A filter is a piece of unit-operations equipment by which filtration is performed. The filter medium or septum is the barrier that lets the liquid pass while retaining most of the solids; it may be a screen, cloth, paper, or bed of solids. The liquid that passes through the filter medium is called the filtrate.

2.3.1 Criteria to Classified Filtration Processes as Following:

2.3.1.1 Location of Particle Retention

The particles can be separated on the outer surface of the filter medium (surface filtration, cake filtration) or inside of the filter medium (depth filtration, deep bed filtration)

2.3.1.2 Generation of the Pressure Difference

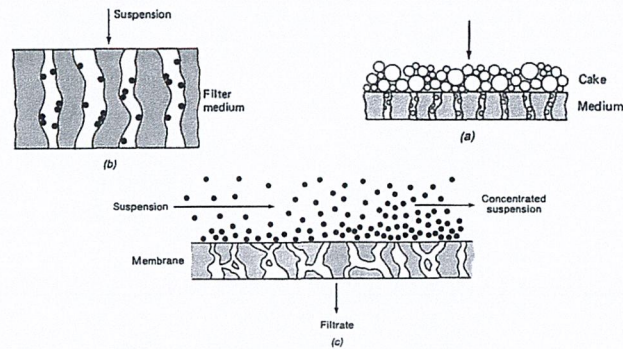
Pressure filtration, vacuum filtration, gravity filtration, centrifugal filtration

2.3.1.3 Operation Mode

Discontinuous, continuous, quasi-continuous. Dynamic filtration and static (normal) filtration. In case of dynamic filtration are during the filtration process mechanisms active which helps to reduce the buildup of a filter cake. The most common dynamic filtration process is cross-flow-filtration

2.3.1.4 Application

For example water filtration, beer filtration



(a) cake filter; (b) clarifying filter; (c) cross flow filter.

Figure 2.2 Filtration Mechanisms (Palmer, J. and Johnson, K.M., 1989)

Slurry from reactor need filter to separate gypsum. In addition vacuum system is required to increase separation rate. Filter used porous or membrane that retain the solids on filter medium. Filtration mechanisms as shown in Figure 2.2. Filter that suitable for gypsum separation is tilting pan filter. Tilting pan filter (as show in Figure 2.3) is a modification of the table or pan filter in which each of the sectors is an individual pan pivoted on a radial axis to allow its inversion for cake discharge, usually assisted by an air blast. Filter cake thicknesses of 50 to 100 mm (2 to 4 in) are common. Most applications involve free-draining inorganic-salt dewatering. In addition to the advantages and disadvantages common to all horizontal continuous filters, tilting-pan filters have the relative advantages of complete wash containment per sector, good cake discharge, filter medium washing, and feasibility of construction in very large sizes, up to about 25 m (80 ft.) in diameter, with about 75 percent of the area usable. Relative disadvantages are high capital cost (especially in smaller sizes) and mechanical complexity leading to higher maintenance costs.

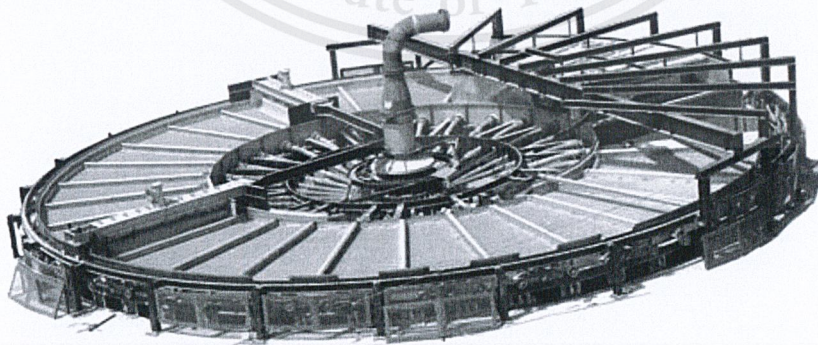


Figure 2.3 Tilting Pan Filter (Prayon, 2016)

2.3.2 Factors Influencing Filtration

2.3.2.1 Vacuum or Pressure

The vast majority of all continuous filters use vacuum to provide the driving force for filtration. However, if the feed slurry contains a highly volatile liquid phase, or if it is hot, saturated, and/or near the atmospheric pressure boiling point, the use of pressure for the driving force may be required. Pressure filtration might also be used where the required cake moisture content is lower than that obtainable with vacuum.

2.3.2.2 Cake Discharge

For any filter application to be practical, it must be possible to produce a cake thick enough to discharge. Table 2.4 tabulates the minimum acceptable cake thickness required for discharge for various types of filters and discharge mechanisms. The experimenter, when running small-scale tests, should decide early in the test program which type of discharge is applicable and then tailor the data collected to fit the physical requirements of that type of unit. Note, however, that the data correlations recommended later are sufficiently general in nature to apply to most equipment types.

Table 2.4 Minimum Cake Thickness for Discharge [Perry, R. H., and Green, D.W., 2008]

Filter type	Minimum design thickness	
	mm	in
Drum		
Belt	3–5	1/8–3/16
Roll discharge	1	1/32
Std. scraper	6	1/4
Coil	3–5	1/8–3/16
String discharge	6	1/4
Precoat	0–3 max.	0–1/8 max.
Horizontal belt	3–5	1/8–3/16
Horizontal table	20	3/4
Tilting pan	20–25	3/4–1
Disk	10–13	3/8–1/2

2.3.2.3 Feed Slurry Temperature

As temperature of the feed slurry is increased, the viscosity of the liquid phase is decreased, causing an increase in filtration rate and a decrease in cake moisture content.

The limit to the benefits of increased temperature occurs when the vapor pressure of the liquid phase starts to materially reduce the allowable vacuum.

2.3.2.4 Cake Thickness Control

Cake thickness must frequently be restricted when cake washing is required or the final cake moisture content is critical. Where the time required for cake washing is the rate-controlling step in the filter cycle, maximum filtration rate will be obtained when using the minimum cake thickness that gives good cake discharge.

2.3.2.5 Filter Cycle

Each filter cycle is composed of cake formation plus one more of the following operations: deliquoring (dewatering or drying), washing, thermal drying, steam drying, and cake discharge. The number of these operations required by a given filtration operation depends upon the process flow sheet. It is neither possible nor necessary to consider all of these operations at once. The basic testing program is designed to look at each operation.

2.3.2.6 Feed Solids Concentration

Feed slurries that are so dilute that they settle rapidly usually yield reduced solids filtration rates and produce stratified cakes with higher moisture contents than would normally be obtained with a homogeneous cake. It is well known that an increase in feed solids concentration is generally an effective means of increasing solids filtration rate, assisting in forming a homogeneous suspension and thereby minimizing cake moisture content.

2.3.2.7 Cloth Blinding

Continuous filters, except for precoats, generally use some type of medium to effect the separation of the solid and filtrate phases. Since the medium is in contact with the process solids, there is always the danger, and almost invariably the actual occurrence, of medium blinding. The term blinding refers to blockage of the fabric itself, either by the wedging of process solids or by solids precipitated in and around the yarn.

2.4 Evaporator (APV, 2008, GEA, 2012)

Water removal from municipal and industrial effluent streams constitutes an important step in wastewater and sludge treatment. The purpose is to concentrate, separate, dispose, or utilize wastes and pollutants and to regenerate and return clean water to the environment. Evaporation is the process by which water (and other liquids) changes from a liquid state to a vapor or gas state. Evaporation is great for separating a mixture (solution) of a soluble solid and a solvent. The process involves heating the solution until the solvent evaporates (turns into gas) leaving behind the solid residue. Here is a simple example involving a mixture of salt and water.

Evaporation is the process by which water (and other liquids) changes from a liquid state to a vapor or gas state. Evaporation is great for separating a mixture (solution) of a soluble solid and a solvent. The process involves heating the solution until the solvent evaporates (turns into gas) leaving behind the solid residue. The diagram are show in Figure 2.4 and Figure 2.5.

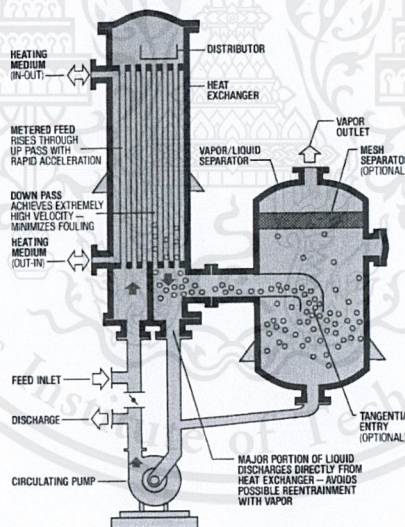


Figure 2.4 Evaporation Separation [APV, 2008]

Mechanical Vapor Recompression (MVR)

Heat is transferred to the fluid to be evaporated. This process indirectly takes place via an evaporator that is used as a heat exchanger. This heat is used to heat the fluid and finally to evaporate the solvent (in most cases water). The heat flow of a single-effect evaporator shows

that the thermal energy included in the vapor (enthalpy) must be about the same as that of the thermal input on the heating side. For the normal case of water evaporation, you can produce 1 kg/h of vapor with 1 kg/h of live steam since the specific evaporation heat is about the same on the product side as on the heating side.

In thermal vapor recompression, motive steam is used to compress part of the vapor produced in an evaporation. Heat of vapor is used to pre heat feed before entry evaporator and more heat is from heater or steam.

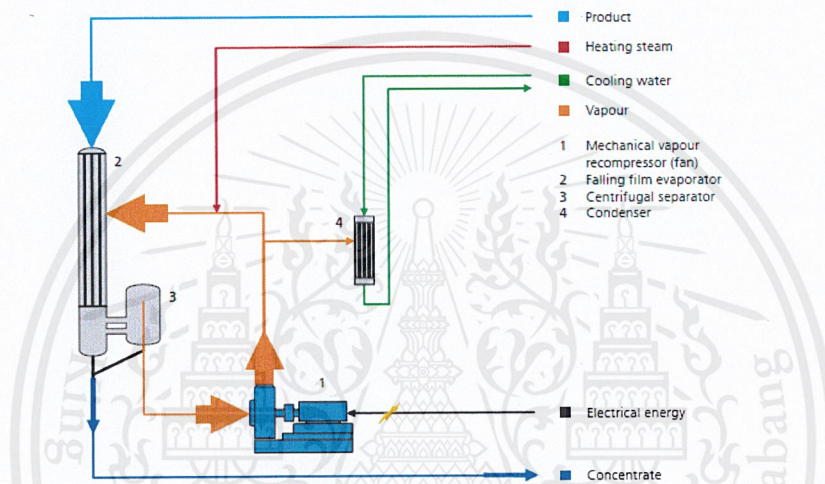


Figure 2.5 Mechanical Vapor Recompression [GEA, 2016]

MVR Benefits

- Steam and overall energy consumption was significantly reduced compared to conventional steam heated evaporator systems with the same capacity.
- Cooling water requirements were reduced
- The main vacuum pump for the evaporator system was reduced in horsepower, capacity and size compared to one required without use of a MVR
- A vacuum pump for the raffinate MVR was not required due to its operation at pressure above atmospheric pressure
- Higher condensate temperatures provide additional steam savings by providing hot water (95-100 °C) source for use in the process.

MVR Disadvantages

- A higher capital cost than a conventional steam heated system
- A MVR could not be utilized on all streams to be evaporated as part of this process.
- High electrical consumption was required with two 1250 HP motors on the raffinate MVR compressors, and these required a high voltage power supply
- Spares such as turbine blades and bearings were required for inventory.

2.5 Cooling Tower [KLM, 2011, John C. H., 2006]

Cooling towers are heat removal devices used to transfer process waste heat to the atmosphere. Cooling towers make use of evaporation whereby some of the water is evaporated into a moving air stream and subsequently discharged into the atmosphere. As a result, the remainder of the water is cooled down significantly.

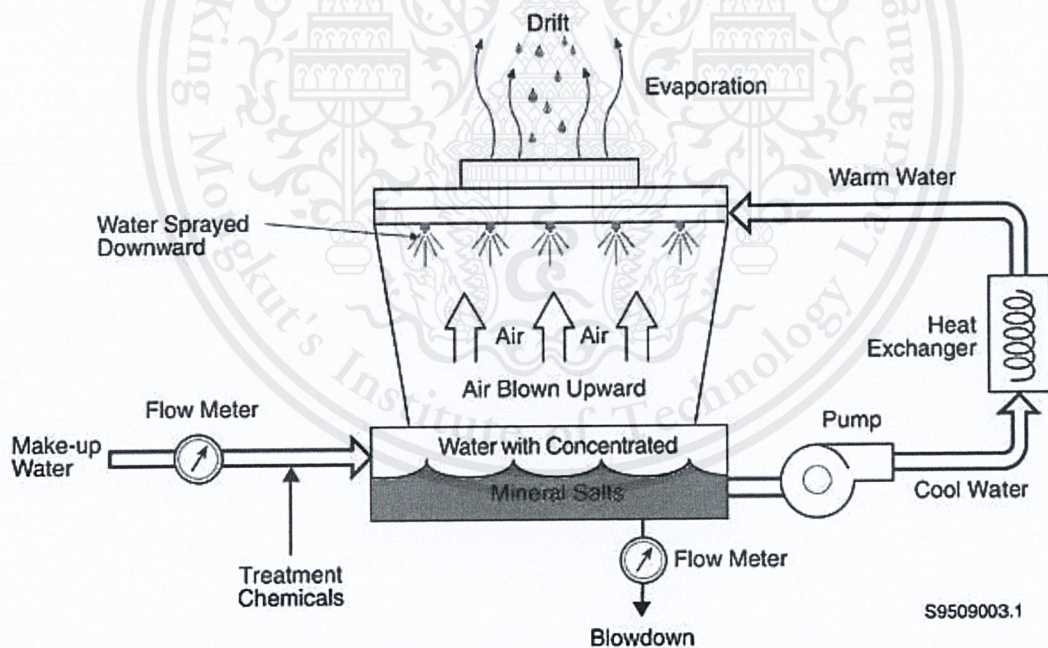


Figure 2.6 Schematic Diagram of a Cooling Water System [KLM, 2011]

There are several important factors that govern the operation of cooling tower:

- The dry-bulb and wet-bulb temperatures of the air

- The temperature of warm water
- The efficiency of contact between air and water in terms of the volumetric mass transfer coefficient and the contact time between the air and the water
- The uniformity of distribution of the phases within the tower
- The air pressure drop
- The desired temperature of the cooled water

Air might enter the tower driven by a density gradient (natural draft), might be pushed into the tower (forced draft) at the base or drawn into the tower (induced draft) assisted by a fan. Several types of cooling towers have been designed on the basis of the above factors and operating strategies.

The cooling tower might be classified into several types, but they are broadly categorized by following considerations:

- Whether there is direct or indirect contact
- The mechanism used to provide the required airflow
- The relative flow paths of air and water
- The primary materials of construction
- the type of heat transfer media applied
- The tower's physical shape

2.5.1 Classification by Build

2.5.1.1 Package Type

This type of cooling towers is preassembled and can be simply transported on trucks as they are compact machines. The capacity of package type towers are limited and for that reason, they are usually preferred by facilities with low heat rejection requirements such as food processing plants, textile plants, buildings like hospitals, hotels, malls, chemical processing plants, automotive factories etc. Due to the intensive use in domestic areas, sound level control is a relatively more important issue for package type cooling towers.

2.5.1.2 Field Erected Type

Field erected type cooling towers are usually preferred for power plants, steel processing plants, petroleum refineries, and petrochemical plants. These towers are larger in size compared to the package type cooling towers.

2.5.2 Classification Based on Heat Transfer Method

2.5.2.1 Wet Cooling Tower

This type of cooling tower operates based on evaporation principle. The working fluid and the evaporated fluid (usually water) are one and the same. In a wet cooling tower, the warm water can be cooled to a temperature lower than the ambient air dry-bulb temperature, if the air is relatively dry.

2.5.2.2 Dry Cooling Tower

This tower operates by heat transfer through a surface that separates the working fluid from ambient air, such as in a tube to air heat exchanger, utilizing convective heat transfer. Dry cooling tower does not use evaporation.

2.5.2.3 Fluid Cooler

This tower passes the working fluid through a tube bundle, upon which clean water is sprayed and a fan-induced draft applied. The resulting heat transfer performance is much closer to that of a wet cooling tower, with the advantage provided by a dry cooler of protecting the working fluid from environmental exposure and contamination.

2.5.3 Classification Based on Air Draft

2.5.3.1 Atmospheric Tower

An atmospheric tower consist of a big rectangular chamber with two opposite louvered walls. The tower is packed with a suitable tower fill. Atmospheric air enters the tower through the louvers driven by its own velocity. An atmospheric tower is cheap but inefficient. Its performance largely depends upon the direction and velocity of wind.

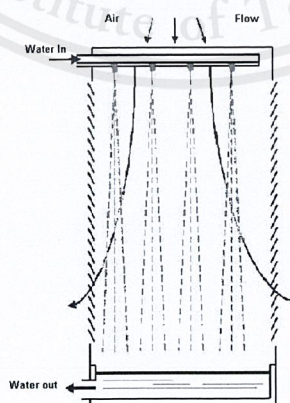


Figure 2.7 Atmospheric Cooling Tower [KLM, 2011]

2.5.3.1 Natural Draft Tower

The natural draft or hyperbolic cooling tower makes use of the difference in temperature between the ambient air and the hotter air inside the tower. As hot air moves upwards through the tower (because hot air rises), fresh cool air is drawn into the tower through an air inlet at the bottom. A natural draft tower is so called because natural flow of air occurs through the tower.

Two factors are responsible for creating the natural draft:

- A rise in temperature and humidity of air in the column reduces its density, and
- The wind velocity at the tower bottom.

Due to the layout of the tower, no fan is required and there is almost no circulation of hot air that could affect the performance. But in some cases, a few fans are installed at the bottom to enhance the air flow rate. This type of tower is called 'fan-assisted' natural draft tower.

The hyperbolic shape is made because of the following reasons:

- More packing can be fitted in the bigger area at the bottom of the shell;
- The entering air gets smoothly directed towards the centre because of the shape of
- The wall, producing a strong upward draft;
- Greater structural strength and stability of the shell is provided by this shape.

The pressure drop across the tower is low and the air velocity above the packing may vary from 1-1.5 m/s. The concrete tower is supported on a set of reinforced concrete columns. Concrete is used for the tower shell with a height of up to 200 m. These cooling towers are mostly only for large heat duties because large concrete structures are expensive.

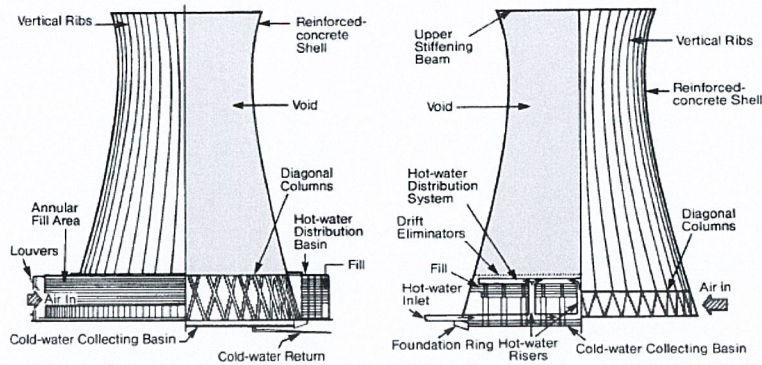


Figure 2.8 (a) Cross Flow and (b) Counter Flow Natural Draft Cooling Tower [KLM, 2011]

2.5.3.2 Mechanical Draft Cooling Tower

Because of their huge shape, construction difficulties and cost, natural draft towers have been replaced by mechanical draft towers in many installations. Mechanical draft towers have large fans to force or draw air through circulated water. The water falls downwards over fill surfaces, which helps increase the contact time between the water and the air. Cooling rates of mechanical draft towers depend upon various parameters; such as fan diameter and speed of operation, fills for system resistance, etc.

There are two different classes of mechanical draft cooling towers:

1. Forced Draft

It has one or more fans located at the tower bottom to push air into the tower. During operation, the fan forces air at a low velocity horizontally through the packing and then vertically against the downward flow of the water that occurs on either side of the fan. The drift eliminators located at the top of the tower remove water entrained in the air. Vibration and noise are minimal since the rotating equipment is built on a solid foundation. The fans handle mostly dry air, greatly reducing erosion and water condensation problems.

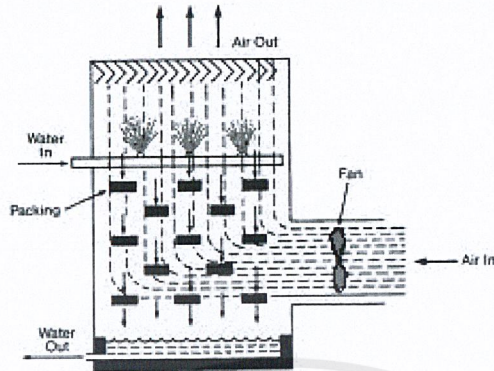


Figure 2.9 Forced Draft Cooling Tower [KLM, 2011]

2. Induced Draft

A mechanical draft tower with a fan at the discharge which pulls air through tower. The fan induces hot moist air out the discharge. This produces low entering and high exiting air velocities, reducing the possibility of recirculation in which discharged air flows back into the air intake.

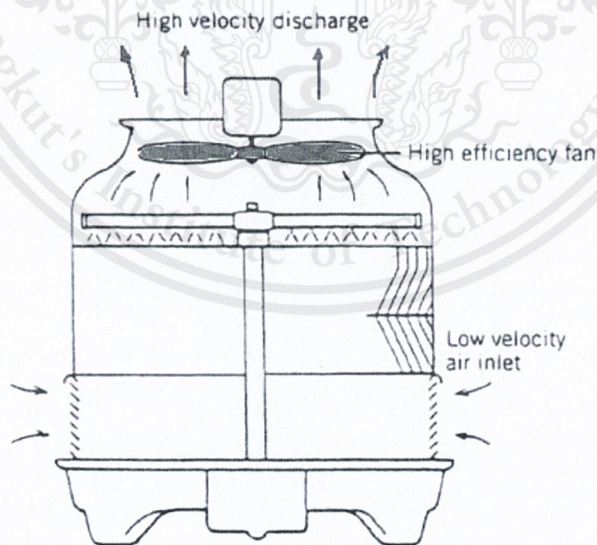


Figure 2.10 Induced Draft Cooling Tower [KLM, 2011]

2.5.4 Classification Based on Air Flow Pattern

2.5.3.1 Cross Flow

Cross flow is a design in which the air flow is directed perpendicular to the water flow. Air flow enters one or more vertical faces of the cooling tower to meet the fill material. Water flows (perpendicular to the air) through the fill by gravity. The air continues through the fill and thus past the water flow into an open plenum area. A distribution or hot water basin consisting of a deep pan with holes or nozzles in the bottom is utilized in a cross flow tower. Gravity distributes the water through the nozzles uniformly across the fill material.

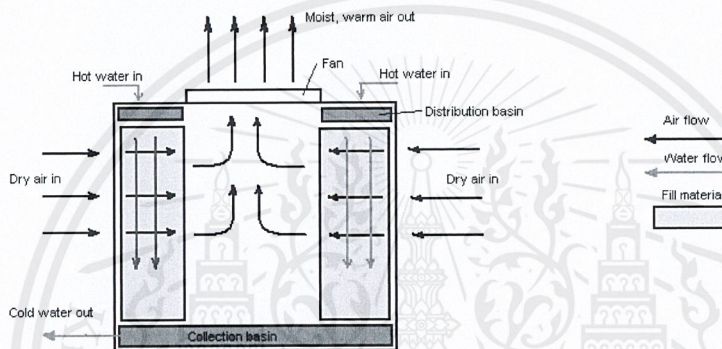


Figure 2.11 Cross Flow type design [KLM, 2011]

2.5.3.2 Counter Flow

In a counter Flow design the air flow is directly opposite to the water flow (see diagram below). Air flow first enters an open area beneath the fill media and is then drawn up vertically. The water is sprayed through pressurized nozzles and flows downward through the fill, opposite to the air flow.

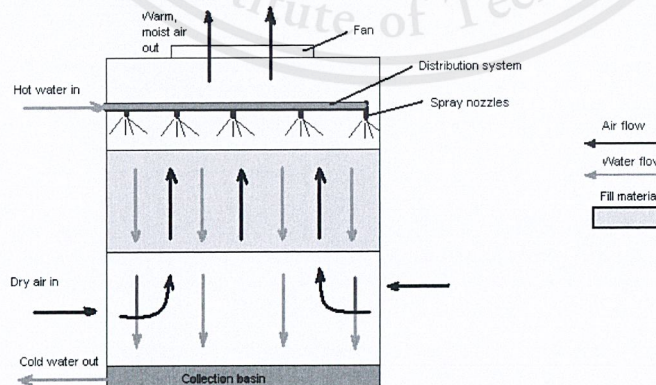


Figure 2.12 Counter Flow Type Design [KLM, 2011]

2.6 Granulator (Bio Impacts, 2015, Valiulis, G. and Simutis, R., 2012)

Drum granulation is a commonly used process in a commercial fertilizer production. Many continuous granulation plants operate well below design capacity, suffering from high recycle rates and even periodic instabilities. The main reasons are related to raw material properties, process equipment and control problems.

Drum granulation is a particle size enlargement process often obtained by spraying a liquid binder or slurry onto fine particles as they are agitated in a rotary drum. The particle circulation is achieved mechanically (by the action of the rotating drum and lifters). Granules are cycled many times through the spray zone and the liquid layer attached is pre-dried before the particle returns to the spray zone again (Figure 2.13).

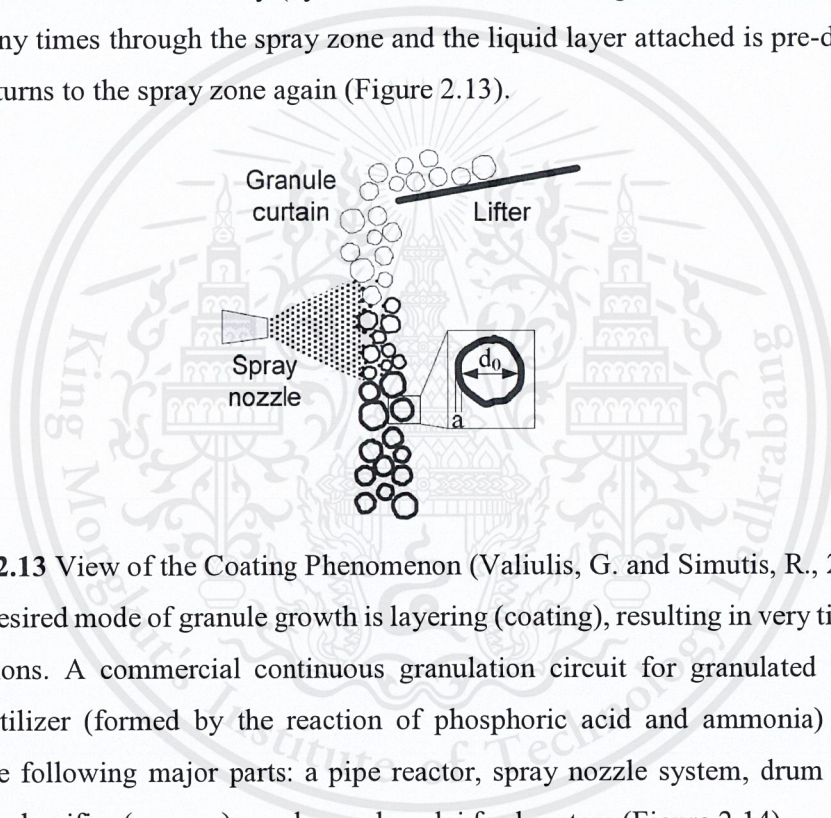


Figure 2.13 View of the Coating Phenomenon (Valiulis, G. and Simutis, R., 2012)

The desired mode of granule growth is layering (coating), resulting in very tight granule size distributions. A commercial continuous granulation circuit for granulated ammonium phosphate fertilizer (formed by the reaction of phosphoric acid and ammonia) production consists of the following major parts: a pipe reactor, spray nozzle system, drum granulator-dryer, granule classifier (screens), crusher and nuclei feed system (Figure 2.14).

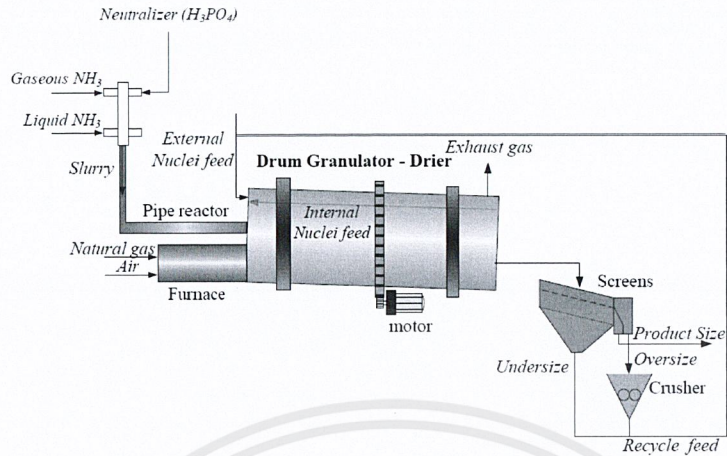


Figure 2.14 Typical Drum Granulation-Drying Circuit Utilized in the Ammonium Phosphate Production Industry (G. Valiulis and R. Simutis, 2012)

A granulation drum is made of an inclined cylinder with simultaneous drying (there is no separate drying device). Drying is performed by the heat of burned natural gas and/or reaction heat of phosphoric acid and ammonia. Liquid AP feed (slurry) is sprayed onto the tumbling bed of seeds via spraying nozzles. The drum is tilted lengthwise a few degrees to provide the flow of granules through the drum length. The backward screw sends a part of granules (internal nuclei) back to the spraying zone. Granules from the granulator-drier are transmitted to the classifier and split into three fractions: undersize, oversize, and marketable product size. The oversize fraction is crushed and sent back to the granulator together with undersize granules.

2.6.1 Dry Granulation Methods

The primary advantages of dry granulation are its simplicity and low cost. There are three common methods. Direct compression, this method simply combines the substance powder with the excipient powders in a blender. The blend then moves directly to a tablet press.

Slugging, in this method, poor-flowing blends are compressed using a rotary tablet press fitted with a die much larger than the die used to make the final tablet, forming “slugs.” Slugs are typically 1 inch in diameter or larger, and there is little attention paid to weight variation or compression properties. Instead, the objective is to make the slug as hard as possible. Next, the slugs pass through a mill, join additional excipients in a blender, and are

transferred to a tablet press filling machine. Occasionally, products require double slugging to densify the mixture enough to obtain the desired flow properties.

Roller compaction, in this method, typically used with moisture-sensitive drug substances and formulations with poor flow characteristics, the material flow between two rollers that compact it. The rollers come in a variety of designs so the formulator can produce compacts of the correct hardness. The compacts are subsequently milled, blended, and made into tablets or filled into capsules. In addition to its ability to process poor-flowing and moisture sensitive materials, roller compaction entails low labor costs and can be adapted for continuous production.

2.6.2 Wet Granulation Methods

Wet granulation methods introduce a fluid onto a shearing mass of fine powders contained in a vessel. Wet granulation equipment includes low-shear and high-shear mixers, fluid-bed processors, rotating drums, and pan mixers. Successfully agglomerating primary particles requires controlling the adhesional forces between particles. It's these forces that encourage agglomerates to form and grow and that determine whether the agglomerates have sufficient mechanical strength. The rheology of the particles before they are agglomerated is sometimes also critical to rearranging them in a way that permits densification of the agglomerate and development of an agglomerate structure that suits end-use requirements.

Granulate Mechanism

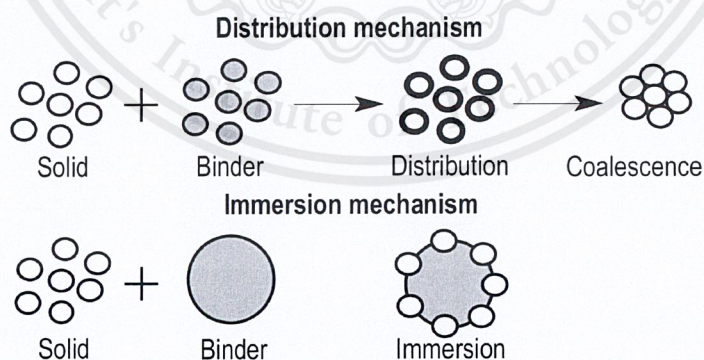


Figure 2.15 the Mechanism of Granulate [Tablets & Capsules, 2007]

Distribution mechanism, this occurs in cases where the binder droplets are small. They coat the primary particles, and the wetted particles coalesce to form initial granules. Low-viscosity binders and high-speed impellers promote the occurrence of this mechanism.

Immersion mechanism, this occurs when binder droplets engulf the primary particles. It commonly occurs when binder viscosity is high and impeller speed is low.

2.7 Drying (Baeyens, J., 2012, Mujumdar, A. S., 2011)

Drying methods and processes can be classified in several different ways. It can be classified as batch, where the material is inserted into the drying equipment and drying proceeds for a given period of time, or as continuous, where the material is continuously added to the dryer and dried material continuously removed.

Drying processes can also be categorized according to the physical conditions used to add heat and remove water vapor. Heat is added by direct contact with heated air at atmospheric pressure, and the water vapor formed is removed by the air; in vacuum drying, the evaporation of water proceeds more rapidly at low pressures, and the heat is added indirectly by contact with a metal wall or by radiation (low temperatures can also be used under vacuum for certain materials that may discolor or decompose at higher temperatures); and in freeze drying, water is sublimed from the frozen material. Dryers expose the solids to a hot surface with which the solid is in contact. Dryers, which expose the solids to a hot gas, are called adiabatic or direct dryers; those in which heat is transferred from an external medium are known as non-adiabatic or indirect dryers. Dryers heated by dielectric, radiant, or microwave energy are also non-adiabatic. Some units combine adiabatic and non-adiabatic drying; they are known as direct-indirect dryers.

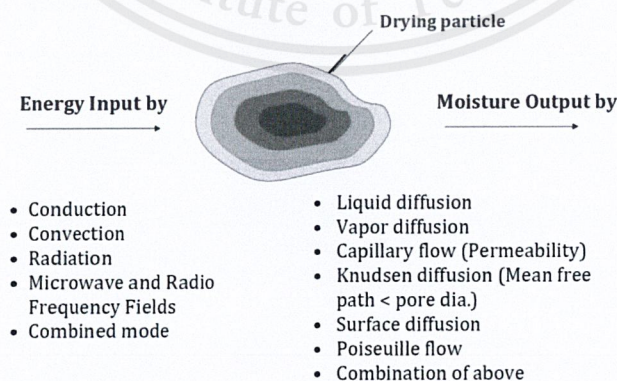


Figure 2.16 Fundamentals of Drying [Mujumdar, A. S., 2011]

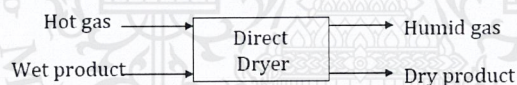
Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer:

- Liquid diffusion, if the wet solid is at a temperature below the boiling point of the liquid
- Vapor diffusion, if the liquid vaporizes within material
- Knudsen diffusion, if drying takes place at very low temperatures and pressures, e.g., in freeze drying
- Surface diffusion (possible although not proven)
- Hydrostatic pressure differences, when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings
- Combinations of the above mechanisms

Note that since the physical structure of the drying solid is subject to change during drying the mechanisms of moisture transfer may also change with elapsed time of drying.

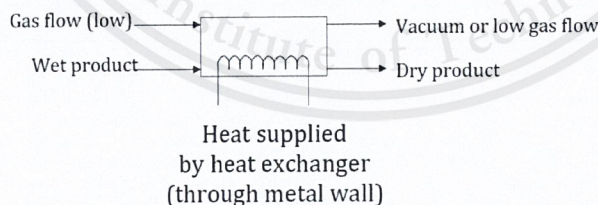
2.7.1 Classification of Drying Based on Heat Input

2.7.1.1 Direct (Convective)

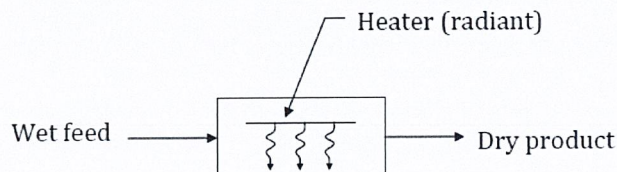


Drying medium directly contacts material to be dried and carries evaporated moisture.

2.7.1.2 Indirect (Contact, Conduction)



2.7.1.3 Radiant



Vacuum or low gas flow to carry evaporated moisture away.

2.7.1.4 Microwave or RF

Electromagnetic energy absorbed selectively by water (volumetric heating)

2.7.2 Equilibrium Moisture Content

The moisture content of a wet solid in equilibrium with air of given humidity and temperature is termed the equilibrium moisture content (EMC). A plot of EMC at a given temperature versus the relative humidity is termed sorption isotherm. Figure 2.10a shows the general shape of the typical sorption isotherms. They are characterized by three distinct zones, A, B and C, which are indicative of different water binding mechanisms at individual sites on the solid matrix. In region A, water is tightly bound to the sites and is unavailable for reaction. In this region, there is essentially monolayer adsorption of water vapor and no distinction exists between the adsorption and desorption isotherms. In region B, the water is more loosely bound. The vapor pressure depression below the equilibrium vapor pressure of water at the same temperature is due to its confinement in smaller capillaries. Water in region C is even more loosely held in larger capillaries. It is available for reactions and as a solvent.

Figure 2.10b shows schematically the shapes of the equilibrium moisture curves for various types of solids. Desorption isotherms are also dependent on external pressure. However, in all practical cases of interest, this effect may be neglected.

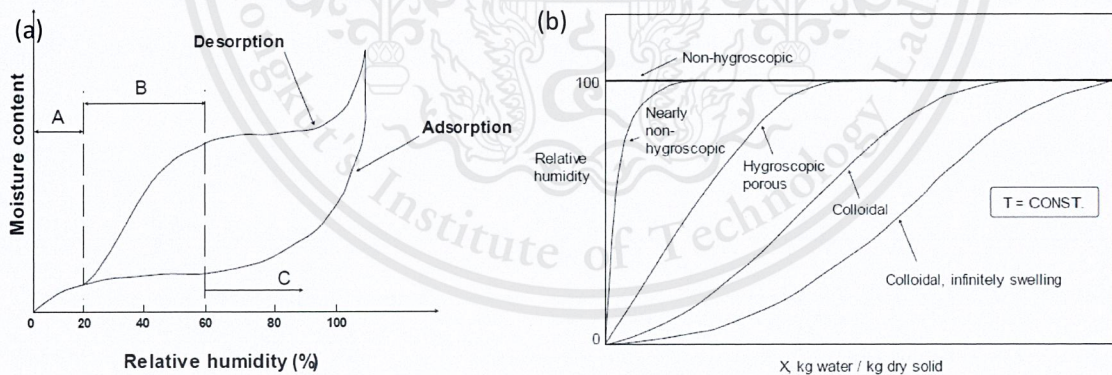


Figure 2.17 (a) Typical Sorption Isotherms and (b) Equilibrium Moisture Content Curves for Various Types of Solids [Arun, S. M. and Sakamon D., 2006]

2.7.3 Rotary Dryers

For the continuous drying of materials on a large scale, 0.3 kg/s (1 tone/h) or greater, a rotary dryer, which consists of a relatively long cylindrical shell mounted on rollers and driven at a low speed, up to 0.4 Hz is suitable. The shell is supported at a small angle to the horizontal

so that material fed in at the higher end will travel through the dryer under gravity, and hot gases or air used as the drying medium are fed in either at the upper end of the dryer to give co-current flow or at the discharge end of the machine to give countercurrent flow. One of two methods of heating is used:

- a) Direct heating, where the hot gases or air pass through the material in the dryer.
- b) Indirect heating, where the material is in an inner shell, heated externally by hot gases. Alternatively, steam may be fed to a series of tubes inside the shell of the dryer.

The shell of a rotary dryer is usually constructed by welding rolled plate, thick enough for the transmission of the torque required to cause rotation, and to support its own weight and the weight of material in the dryer. The shell is usually supported on large types which run on wide rollers, as shown in Figure 2.18, and although mild steel is the usual material of construction, alloy steels are used, and if necessary the shell may be coated with a plastics material to avoid contamination of the product.

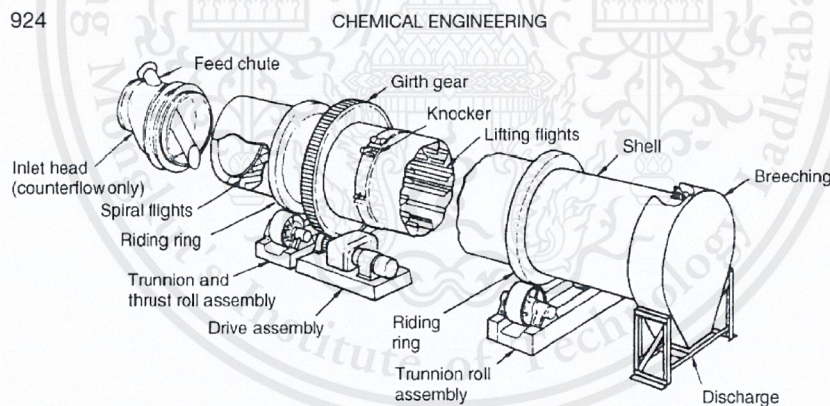


Figure 2.18 Configuration of Rotary Dryer [Baeyens, J., 2012]

2.8 Cyclone

Cyclones provide a relatively low-cost method of removing particulate matter from exhaust gas streams. Cyclones are somewhat more complicated in design than simple gravity settling systems, and their removal efficiency is accordingly much better than that of settling chambers. However, cyclones are not as efficient as electrostatic precipitators, baghouses, and venturi scrubbers but are often installed as pre cleaners before these more effective devices.

Cyclones come in many sizes and shapes and have no moving parts. The basic separation principle remains the same others. Particles enter the device with the flowing gas (Figure 2.19); the gas stream is forced to turn, but the larger particles have more momentum and cannot turn with the gas. These larger particles impact and fall down the cyclone wall and are collected in a hopper. The gas stream actually turns a number of times in a helical pattern, much like the funnel of a tornado. The repeated turnings provide many opportunities for particles to pass through the streamlines, thus hitting the cyclone wall.

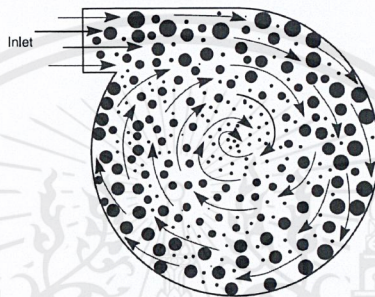


Figure 2.19 Particle Collection Process. [Theodore, L., 2008]

Three types of cyclones are shown in Figure 2.20. The first diagram, Figure 2.20a shows a typical tangential entry cyclone arrangement. These cyclones have a distinctive and easily recognized form and can be found in almost any industrial area of a town or a city—at lumber companies, feed mills, cement plants, power plants, smelters, and at many other process industrial sites. Since top inlet-type cyclones are so widely used, most of this chapter will be devoted to their operational characteristics.

In axial entry cyclones, Figure 2.20b, the gas inlet is parallel to the axis of the cyclone body. Here, the exhaust process gases enter from the top and are directed into a vortex pattern by the vanes attached to the central tube. Axial entry cyclones are commonly used in multi cyclone configurations; these units generally provide higher efficiencies.

The larger cyclonic-type separator shown in Figure 2.20c is often used after wet scrubbers to collect particulate matter entrained in water droplets. The gas enters tangentially at the bottom of the unit, forming a vortex. The large water droplets are forced against the walls and are removed from the gas stream.

Consider the dimensions shown in Figure 2.20d. Configuration of cyclone is followed model that shown in Table 2.4. Each model affect to collection efficiency and economic.

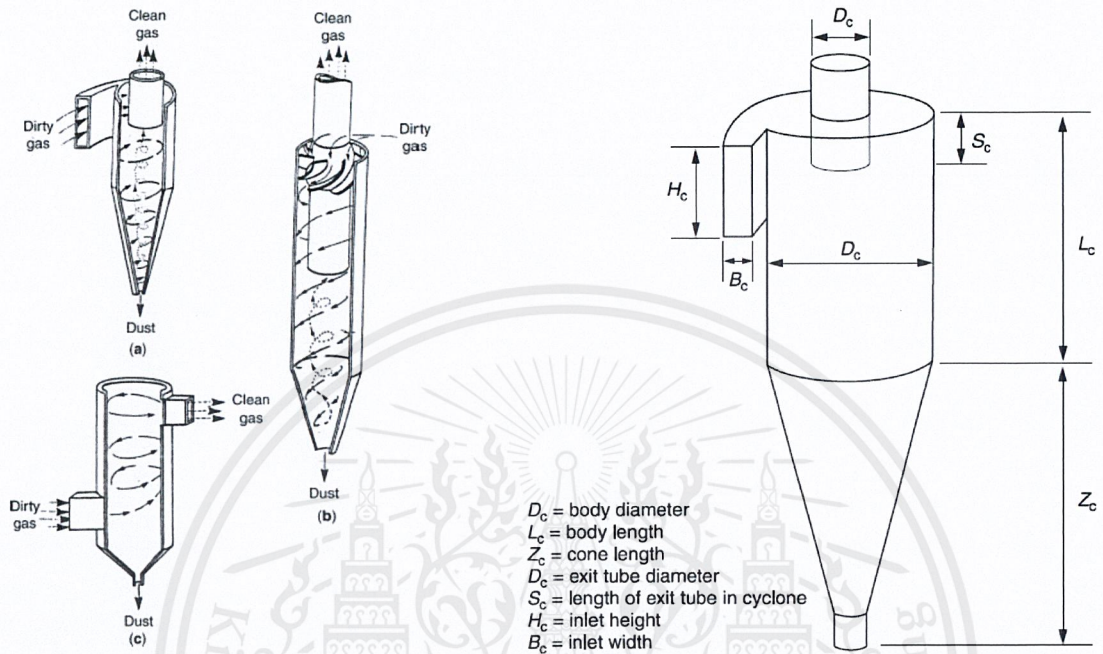


Figure 2.20 Types of Cyclones: (a) Top Inlet; (b) Axial Inlet; (c) Bottom Inlet and (d) Nomenclature for a Tangential Entry Cyclone [Theodore, L., 2008]

Table 2.5 Geometric Specifications for the Design of a Cyclone Separator [Theodore, L., 2008]

Term	Description	Stairmand	Swift	Laple	Parnell
H_c/D_c	Inlet Height	0.50	0.44	0.50	0.50
B_c/D_c	Inlet Width	0.20	0.21	0.25	0.25
S_c/D_c	Outlet Length	0.00	0.06	0.13	0.13
D_e/D_c	Outlet Diameter	0.50	0.40	0.50	0.63
L_c/D_c	Cylinder Height	1.50	1.40	2.00	1.00
Z_c/D_c	Overall Height	3.00	2.50	2.00	2.00
J_c/D_c	Dust Outlet	0.38	0.40	0.25	0.50

2.8.1 Design and Performance Equations

Objects moving in circular paths tend to move away from the center of their motion. The object moves outward as if a force is pushing it out. This force is known as centrifugal

force. The whirling motion of the gas in a cyclone causes particulate matter in the gas to sense this force and move out to the walls.

$$F = \frac{\rho_p d_p^3 v_p^2}{r} \quad (\text{Eq. 2.13})$$

2.8.2 Cut Diameter

The cut diameter is defined as the size (diameter) of particles collected with 50% efficiency. It is a convenient way of defining efficiency for a control device since it provides information on the effectiveness for a particle size range.

$$d_{pc} = \left(\frac{9\mu W}{2\pi N_s v_i (\rho_p - \rho_g)} \right)^{0.5} \quad (\text{Eq. 2.14})$$

The cut diameter, d_{pc} or $[d_p]_{\text{cut}}$, is a characteristic of the control device and should not be confused with the geometric mean particle diameter, d_{gm} , of the size distribution.

Figure 2.21 shows a size efficiency curve and points out the cut diameter and the critical diameter, $[d_p]_{\text{crit}}$, the particle size collected at 100% efficiency. Values of $[d_p]_{\text{crit}}$ are difficult to obtain from such curves so the cut size is often determined instead.

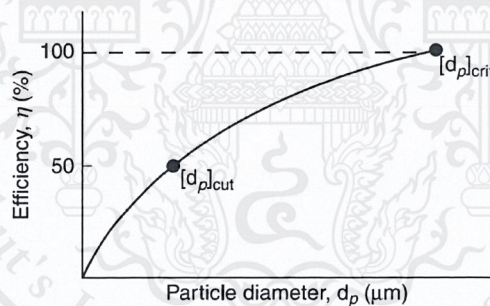


Figure 2.21 Typical Size Efficiency Curve [Sakura, G. B. and Andrew, Y. T., 2015]

2.8.3 Collection Efficiency

A number of equations have been developed for determining the fractional cyclone efficiency, E_i for a given size particle. As noted earlier, fractional efficiency is defined as the fraction of particles of a given size collected in the cyclone, compared to those of that size going into the cyclone.

No efficiency theory or calculation method provides a description for all cyclones. The modification of inlets and outlets, addition of fines educators, etc., introduce variables that are difficult to treat theoretically. Although theoretical efficiencies can give estimations of

cyclone performance, it should be kept in mind that designers of equipment commonly rely on comparative evaluations between similar designs and on experience.

$$\eta = \frac{1}{1 + \left(\frac{d_{pc}}{d_p}\right)^2} \quad (\text{Eq. 2.15})$$

2.8.3 Pressure Drop

The pressure drop across a cyclone is an important parameter to the purchaser of such equipment. Increased pressure drop means greater costs for power to move an exhaust gas through the control device. With cyclones, an increase in pressure drop usually means that there will be an improvement in collection efficiency (one exception to this is the use of pressure recovery devices attached to the exit tube; these reduce the pressure drop but do not adversely affect collection efficiency). For these reasons, there have been many attempts to predict pressure drops from design variables. The idea is that having such an equation, one could work back and optimize the design of new cyclones.

2.8.3.1 Inlet Contraction

This loss is primarily associated with cyclones inside a vessel. If the cyclone is connected outside a vessel, the d_p tap may measure acceleration, and this term should not be used for total d_p .

$$\Delta P_i = 0.5 \rho_g (v_{in}^2 - v_{vessel}^2 + K v_{in}^2) \quad (\text{Eq. 2.16})$$

3.8.3.2 Particle Acceleration

$$\Delta P_p = L v_{in} (v_{pin} - v_{pvessel}) \quad (\text{Eq. 2.17})$$

For small particles, the velocity is taken as equal to the gas velocity.

3.8.3.3 Pressure Drop of Barrel Friction

$$\Delta P_b = \frac{2f \rho_g v_{in}^2 \pi D_c N_s}{d_{in}} \quad (\text{Eq. 2.18})$$

The Reynolds number for determining the friction factor f is based on the inlet area.

3.8.3.4 Pressure Drop of Gas Flow Reversal

$$\Delta P_g = \frac{\rho_g v_{in}^2}{2} \quad (\text{Eq. 2.19})$$

3.8.3.5 Pressure Drop of Exit Contraction

$$\Delta P_e = 0.5\rho_g(v_{exit}^2 - v_c^2 + K v_{exit}^2) \quad (\text{Eq. 2.20})$$

However, the actual pressure drop observed turns out to be a function of the solids loading. The pressure drop is high when the gas is free of solids and then decreases as the solids loading increases up to about 3 kg/m³ (0.2 lb/ft³). The cyclone d_p then begins to increase with loading. The cause of the initial decline is that the presence of solids decreases the tangential velocity of the gas.

2.9 Scrubber [Theodore, L., 2008]

Gas absorbers are used extensively in industry for separation and purification of gas streams, as product recovery devices, and as pollution control devices. Absorption is a process where one or more soluble components of a gas mixture are dissolved in a liquid (i.e., a solvent). The absorption process can be categorized as physical or chemical. Physical absorption occurs when the absorbed compound dissolves in the solvent; chemical absorption occurs when the absorbed compound and the solvent react. Liquids commonly used as solvents include water, mineral oils, nonvolatile hydrocarbon oils, and aqueous solutions.

Absorption is a mass transfer operation in which one or more soluble components of a gas mixture are dissolved in a liquid that has low volatility under the process conditions. The pollutant diffuses from the gas into the liquid when the liquid contains less than the equilibrium concentration of the gaseous component. The difference between the actual concentration and the equilibrium concentration provides the driving force for absorption.

2.9.1 Packed Tower Internals

A basic packed tower unit is comprised of a column shell, mist eliminator, liquid distributors, packing materials, packing support, and may include a packing restrainer. Corrosion resistant alloys or plastic materials such as polypropylene are required for column internals when highly corrosive solvents or gases are used. A schematic drawing of a countercurrent packed tower is shown in Figure 2.22. In this figure, the packing is separated into two sections. This configuration is more expensive than designs where the packing is not so divided.

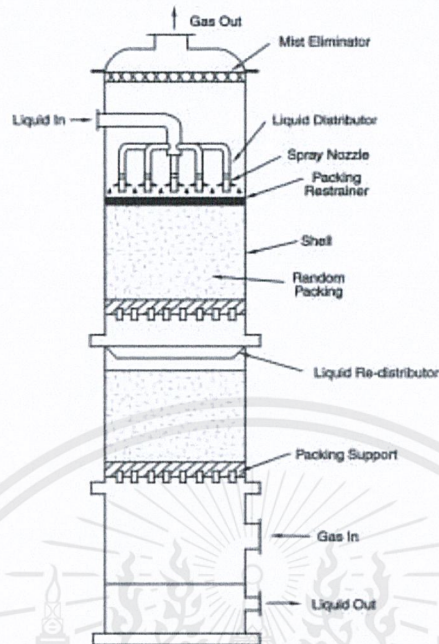


Figure 2.22 Packed Tower for Gas Absorption [Theodore, L., 2008]

The tower shell may be made of steel or plastic, or a combination of these materials depending on the corrosiveness of the gas and liquid streams, and the process operating conditions.

One alloy that is chemical and temperature resistant or multiple layers of different, less expensive materials may be used. The shell is sometimes lined with a protective membrane, often made from a corrosion resistant polymer. For absorption involving acid gases, an interior layer of acid resistant brick provides additional chemical and temperature resistance.

At high gas velocities, the gas exiting the top of the column may carry off droplets of liquid as a mist. To prevent this, a mist eliminator in the form of corrugated sheets or a layer of mesh can be installed at the top of the column to collect the liquid droplets, which coalesce and fall back into the column.

A liquid distributor is designed to wet the packing bed evenly and initiate uniform contact between the liquid and vapor. The liquid distributor must spread the liquid uniformly, resist plugging and fouling, provide free space for gas flow, and allow operating flexibility. Large towers frequently have a liquid redistributor to collect liquid off the column wall and direct it toward the center of the column for redistribution and enhanced contact in the lower

section of packing. Liquid redistributors are generally required for every 8 to 20 feet of random packing depth.

Packing materials provide a large wetted surface for the gas stream maximizing the area available for mass transfer. Packing materials are available in a variety of forms, each having specific characteristics with respect to surface area, pressure drop, weight, corrosion resistance, and cost. Packing life varies depending on the application. In ideal circumstances, packing will last as long as the tower itself. In adverse environments packing life may be as short as 1 to 5 years due to corrosion, fouling, and breakage.

Packing materials are categorized as random or structured. Random packings are usually dumped into an absorption column and allowed to settle. Modern random packings consist of engineered shapes intended to maximize surface-to-volume ratio and minimize pressure drop. Examples of different random packings are presented in Figure 2.23. The first random packings specifically designed for absorption towers were made of ceramic. The use of ceramic has declined because of their brittleness, and the current markets are dominated by metal and plastic. Metal packings cannot be used for highly corrosive pollutants, such as acid gas, and plastic packings are not suitable for high temperature applications. Both plastic and metal packings are generally limited to an unsupported depth of 20 to 25. At higher depths the weight may deform the packing.

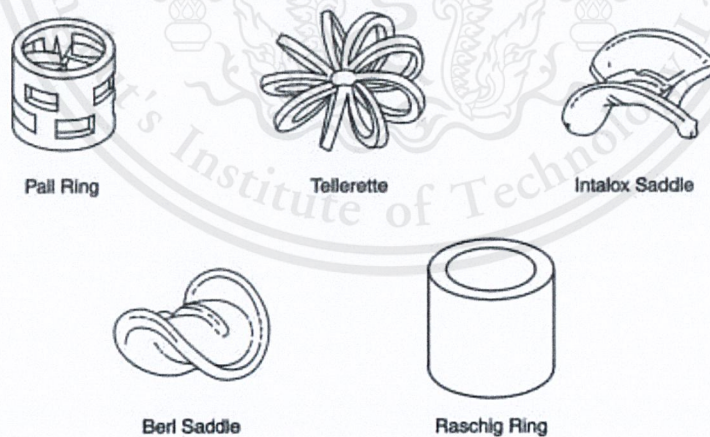


Figure 2.23 Random Packing Material [Theodore, L., 2008]

Structured packing may be random packings connected in an orderly arrangement, interlocking grids, or knitted or woven wire screen shaped into cylinders or gauze like

arrangements. They usually have smaller pressure drops and are able to handle greater solvent flow rates than random packings. However, structured packings are more costly to install and may not be practical for smaller columns. Most structured packings are made from metal or plastic.

2.9.2 Liquid-to-Gas Ratio

The liquid-to-gas ratio (L/G) is the volume of liquid injected per volume of waste gas treated. In general, a higher L/G ratio increases collection efficiency since the density of droplets across a given cross-section of the venturi is higher. Liquid flow rates between 7 and 10 gal/1000 ft³ give optimum performance. L/G ratios in this range produce fairly constant collection efficiencies given a constant pressure drop. L/G ratios of greater than 10 gal/1000 ft³ do not improve the scrubber performance significantly. While increasing the L/G ratio increases collection efficiency, operating costs are increased as well due to greater scrubbing liquid and pump usage.

The liquid flow rate entering the absorber, L_i (gpm), is then calculated using a graphical method. Figure 2.24 presents an example of an equilibrium curve and operating line. The equilibrium curve indicates the relationship between the concentration of pollutant in the waste gas and the concentration of pollutant in the solvent at a specified temperature. The operating line indicates the relation between the concentration of the pollutant in the gas and solvent at any location in the gas absorber column. The vertical distance between the operating line and equilibrium curve indicates the driving force for diffusion of the pollutant between the gas and liquid phases. The minimum amount of liquid which can be used to absorb the pollutant in the gas stream corresponds to an operating line drawn from the outlet concentration in the gas stream (Y_o) and the inlet concentration in the solvent stream (X_i) to the point on the equilibrium curve corresponding to the entering pollutant concentration in the gas stream (Y_i). At the intersection point on the equilibrium curve, the diffusional driving forces are zero, the required time of contact for the concentration change is infinite, and an infinitely tall tower results.

The slope of the operating line intersecting the equilibrium curve is equal to the minimum L/G ratio on a moles of pollutant-free solvent (L_s) per moles of pollutant-free gas basis G_s . in other words, the values L_s and G_s do not include the moles of pollutant in the liquid

CHAPTER III

RESEARCH METHODOLOGY

The research methodology has 3 parts that are mass and energy balance of fertilizer plant, rotary dryer calculation, cyclone calculation and packed bed scrubber calculation. Mass balance is process line calculation for design equipment. Rotary dryer calculation finds heat consumption that uses to issue combustion chamber data sheet. Cyclone is used for dust collection that must be verified by calculation. The cyclone configuration and results are used to issue cyclone data sheet. Liquid flow rate in scrubber is verified in packed bed scrubber calculation. Moreover volume of packing are compared with vendor.

3.1 Mass and Energy Balance of Fertilizer Plant

3.1.1 Study overall process of fertilizer plant (PFDs of phosphoric acid and ammonium phosphate processes) to produce ammonium phosphate fertilizer

3.1.2 Study phosphoric acid reaction and superphosphate reaction

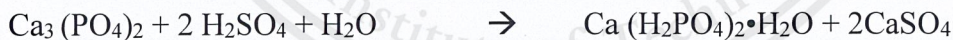
Wet process reaction is



Superphosphate reactions; first is tri superphosphate (TSP)



And second is single superphosphate (SSP)



3.1.3 Study working of each unit (Phosphoric acid reactor, filter, evaporator, acidic cooling tower, super phosphate reactor, granulator, rotary dryer, screener, cooler and coating drum) in fertilizer plant

3.1.4 Calculate mass and energy balance

3.1.4.1 Mass and energy balance of phosphoric acid reactor based on reaction

3.1.4.2 Mass balance of filter to separate gypsum that has 80% moisture

- 3.1.4.3 Mass and energy balance of evaporator to increase concentration from 25 to 42 wt% of P_2O_5
- 3.1.4.4 Mass and energy balance of acidic cooling tower to supply cooling water in reactor, filter and evaporator condenser
- 3.1.4.5 Mass and energy balance of TSP/SSP reactor by phosphate feeding at 8.4 ton/h; Phosphate is fed to TSP and SSP at 4.2 ton/h
- 3.1.4.6 Mass balance of granulator for product that contain of 5 wt% of nitrogen and 39 wt% of phosphorous pentoxide
- 3.1.4.7 Mass and energy balance of dryer for 2 wt% moisture of product
- 3.1.4.8 Mass and energy balances of screen, cooler and coater
- 3.1.5 Verify template for calculation mass and energy balance by comparison with licensors

3.2 Rotary Dryer Calculation

- 3.2.1 Study principles and working of rotary dryer
- 3.2.2 Collect plant data in vendor's data sheet for dryer calculation
- 3.2.3 Calculate heat capacities of water, steam and air at that conditions

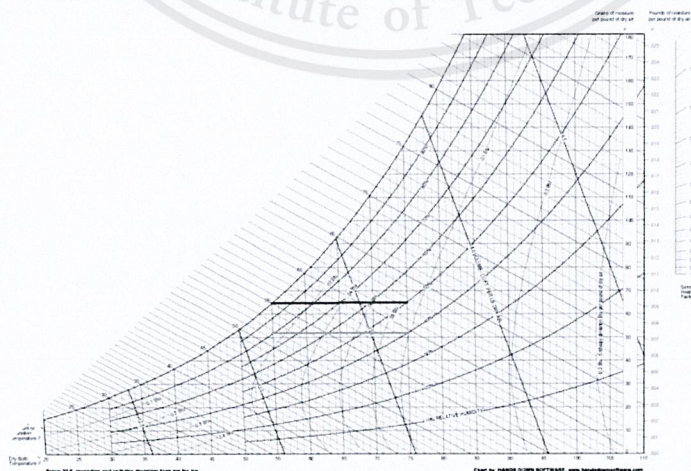


Figure 3.1 Psychrometric Chart [Carrier, 2012]

3.2.4 Find wet bulb temperature to calculate outlet air temperature

3.2.4.1 Use psychometric chart by 2 existing values

3.2.4.2 Use iteration method by guessed initial wet bulb temperature

$$E = \frac{Es \times Rh}{100} \quad (3.1)$$

$$Es = 6.112 \times e^{(17.67 \times T)/(T+243.5)} \quad (3.2)$$

$$Eg = Es - P_{sta} \times (T - T_w) \times 0.00066 \times (1 + (0.00115 T_w)) \quad (3.3)$$

$$Ed = E - Eg \quad (3.4)$$

Vapor pressure and saturated vapor pressure are calculated in first step. Calculation vapor pressure are calculate from initial wet bulb temperature. Difference vapor pressure must be equal to zero for true wet bulb temperature.

3.2.5 Find outlet temperature of exhaust gas

3.2.5.1 Number of transfer units is defined around 1.5-2.5

3.2.5.2 Find outlet air temperature by number of transfer unit's equation

$$NTU = \ln \frac{T_{hb} - T_{wb}}{T_{ha} - T_{wb}} \quad (3.5)$$

3.2.6 Find heat consumption of dryer

$$\frac{q_T}{\dot{m}_s} = \sum c_{pi} \Delta T_i \quad (3.6)$$

3.2.8 Compare results from template and data sheet

3.2.9 Revisionary template and create flowchart for using that is shown in Figure 3.1

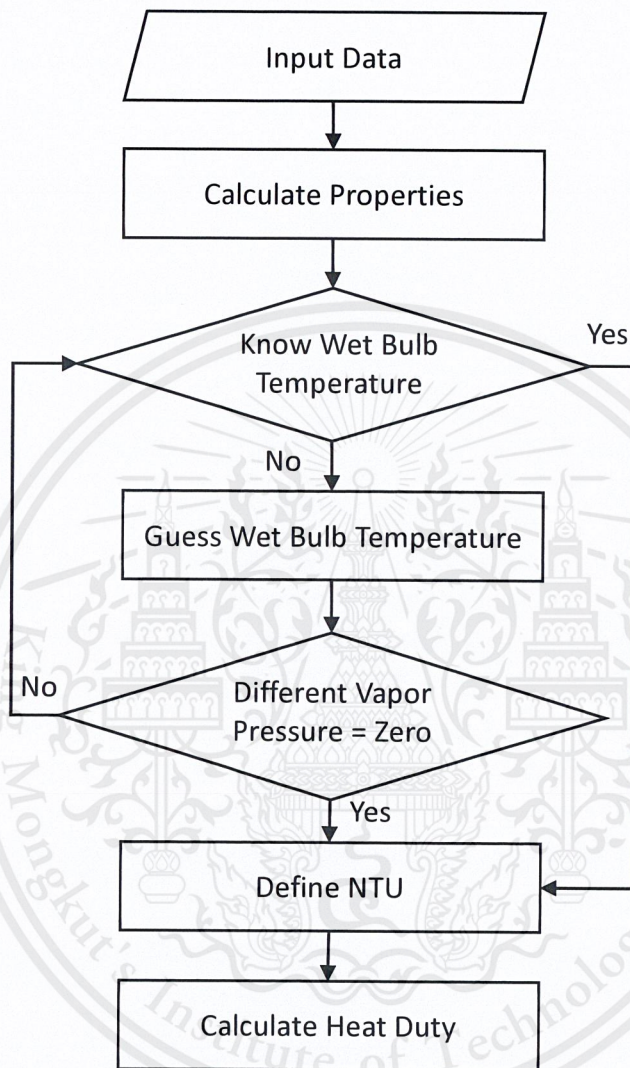


Figure 3.2 Calculation Flow Chart for Rotary Dryer

3.3 Cyclone Calculation

3.3.1 Study principles and working of cyclone

3.3.2 Collect plant data for cyclone calculation by vendor's data sheet

3.3.3 Calculate cyclone configurations by model selection

3.3.3.1 Select cyclone models that are Stairman, Swift, Lapple and Parnell

The model are shown in Table 3.1. Each model is effect to diameter and height that are used to calculate efficiency.

Table 3.1 Cyclone Configuration Models

Term	Description	Stairmand	Swift	Lapple	Parnell
Hc/Dc	Inlet height	0.50	0.44	0.50	0.50
Bc/Dc	Inlet width	0.20	0.21	0.25	0.25
Sc/Dc	Outlet length	0.00	0.06	0.13	0.13
De/Dc	Outlet diameter	0.50	0.40	0.50	0.63
Lc/Dc	Cylinder height	1.50	1.40	2.00	1.00
Zc/Dc	Overall height	3.00	2.50	2.00	2.00
Je/Dc	Dust outlet	0.38	0.40	0.25	0.50

3.3.3.2 Sizing cyclone

The cyclone sizing is following ratio of each model to find area.

$$D_C = \frac{q}{B_C H_C} \quad (3.10)$$

3.3.4 Find collection efficiency

3.3.4.1 Guess air velocity (Air velocity should be between 8-30 m/s)

3.3.4.2 Find cutting diameter that is particle size to collect 50% of dust

$$d_{pc} = \left(\frac{9\mu W}{2\pi N_s v_i (\rho_p - \rho_g)} \right)^{0.5} \quad (3.11)$$

3.3.4.3 Find collection efficiency of each particle size

$$\eta = \frac{1}{1 + \left(\frac{d_{pc}}{d_{pj}} \right)^2} \quad (3.12)$$

Total efficiency based on weight fraction. If calculation collection efficiency is not equal target efficiency, air velocity will be guessed

3.3.5 Check air velocity by using ration of saltation velocity and air velocity

3.3.5.1 Saltation velocity equation

$$v_s = 2.055\omega \left(\frac{(W/D)^{0.4}}{(1-W/D)^{0.333}} \right) D^{0.667} v_i^{0.667} \quad (3.13)$$

$$\text{where } \omega = \left(\frac{4g\mu(\rho_p - \rho_f)}{3\rho_f^2} \right)^{1/3}$$

3.3.5.2 The ratio of saltation velocity and air velocity must be less than 1.25

If v_i/v_s is less than 1.25, this air velocity can be used. Unless v_i/v_s is less than 1.25, Air velocity must be guessed new value. Maximum value of efficiency occur around v_i/v_s equal 1.25 and re entrainment initiate to occur at v_i/v_s is 1.36.

3.3.6 Find pressure drop

3.3.6.1 Pressure drop of inlet contraction

$$\Delta P_i = 0.5\rho_g(v_{in}^2 - v_{vessel}^2 + K v_{in}^2) \quad (3.14)$$

3.3.6.2 Pressure drop of particle acceleration

$$\Delta P_p = L v_{in} (v_{pin} - v_{pvessel}) \quad (3.15)$$

3.3.6.3 Pressure drop of barrel friction

$$\Delta P_b = \frac{2f\rho_g v_{in}^2 \pi D_c N_s}{d_{in}} \quad (3.16)$$

$$f = 0.25 \left(\log \left(\frac{e/D}{3.7} + \frac{5.74}{Re^{0.9}} \right) \right)^{-2} \quad (3.17)$$

$$Re = \frac{\rho_g D_c v_g}{\mu_g} \quad (3.18)$$

3.3.6.4 Pressure drop of gas flow reversal

$$\Delta P_g = \frac{\rho_g v_{in}^2}{2} \quad (3.19)$$

3.3.6.5 Pressure drop of exit contraction

$$\Delta P_e = 0.5\rho_g(v_{exit}^2 - v_c^2 + K v_{exit}^2) \quad (3.20)$$

The total pressure drop must be between 250-4000 Pa. If pressure drop is high, dust is hard to separate.

3.3.7 Compare results from template and data sheet

3.3.8 Revisionary template and create flowchart for using that show in Figure 3.2

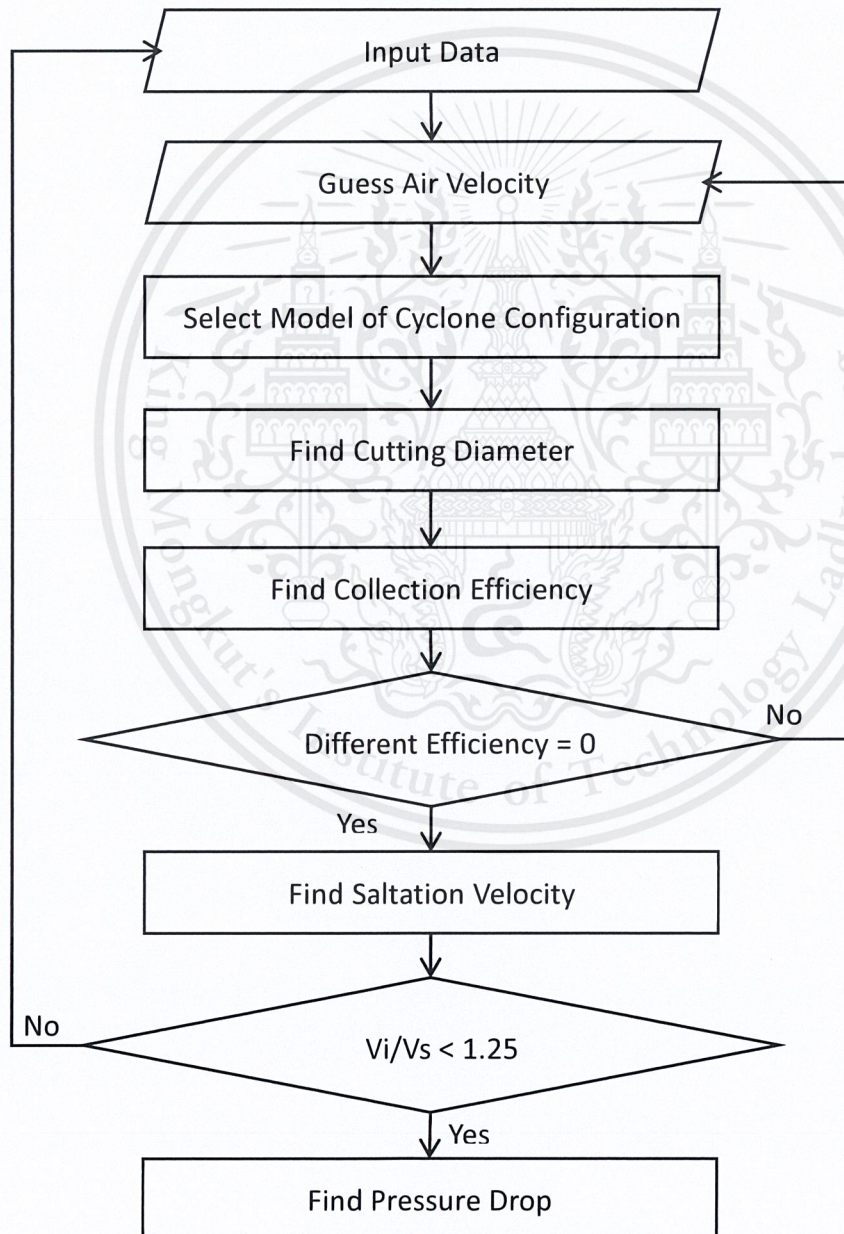


Figure 3.3 Calculation Flow Chart for Cyclone

3.4 Packed Bed Scrubber Calculation

3.4.1 Study principles and working of packed scrubber

3.4.2 Collect plant data for packed scrubber calculation by vendor's data sheet

3.4.3 Calculate liquid flow rate

$$L' \left(\frac{x_0}{1-x_0} \right) + V' \left(\frac{y_2}{1-y_2} \right) = L' \left(\frac{x_1}{1-x_1} \right) + V' \left(\frac{y_1}{1-y_1} \right) \quad (3.21)$$

Mass balance of component is used to find minimum liquid flow rate. Mole fraction of ammonia in outlet gas and inlet liquid are plotted and drag to equilibrium line. Mole fraction of ammonia in outlet water is read at fixed mole fraction of ammonia in inlet gas. Operating liquid flow rate is 1.5 times of minimum liquid flow rate.

3.4.4 Mass flux is calculated to find column diameter

$$\text{Abscissa} = \left(\frac{L}{G} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.5} \quad (3.22)$$

Abscissa is calculated to plot in Figure 3.4 and read ordinate term that is used to calculate flooding mass flux. Operating mass flux is 0.5-0.75 of flooding mass flux.

The mass flux is calculated by equation 3.23

$$G' = \left[\frac{\epsilon \rho_g \rho_l g_c}{F \phi \mu_l^{0.2}} \right]^{0.5} \quad (3.23)$$

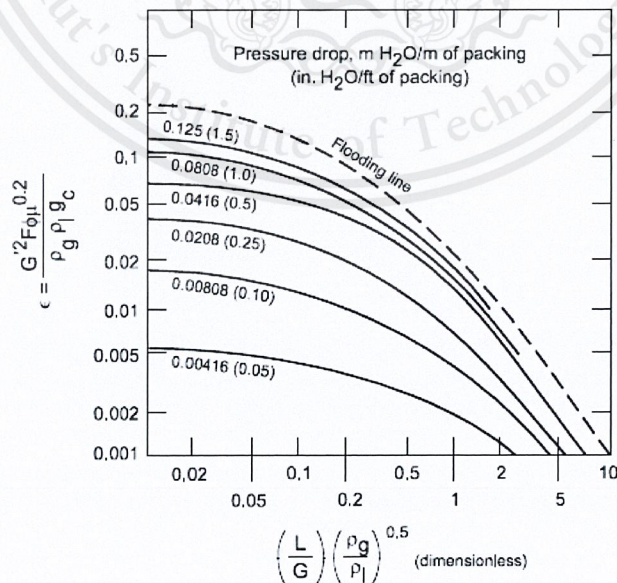


Figure 3.4 Generalized Flooding and Pressure Drop Correlation

3.4.5 Column area is calculated by divided volumetric flow rate by operating mass flux. Column diameter is calculated in equation 3.25

$$A = \frac{G}{G'_{\text{operting}}} \quad (3.24)$$

$$D = \left(\frac{4A}{\pi}\right)^{0.5} \quad (3.25)$$

3.3.6 Packing height is calculated by multiplication of number of transfer units and height of overall transfer units

3.3.6.1 Number of transfer units

$$N_{OG} = \frac{\ln\left(\left(\frac{y_1 - mx_1}{y_2 - mx_1}\right)\left(1 - \frac{mG_m}{L_m}\right) + \left(\frac{mG_m}{L_m}\right)\right)}{1 - \frac{mG_m}{L_m}} \quad (3.26)$$

3.3.6.2 Height of overall transfer units

$$H_{OG} = \frac{G'}{K_{OGAP}} \quad (3.27)$$

3.3.7 Pressure drop in scrubber uses Figure 3.4 that is pressure drop per height of packing. Total pressure drop is multiply pressure drop that read from graph by packing height.

3.3.8 Compare results from template and data sheet

3.3.8 Revisionary template and create flowchart for using that show in Figure 3.4

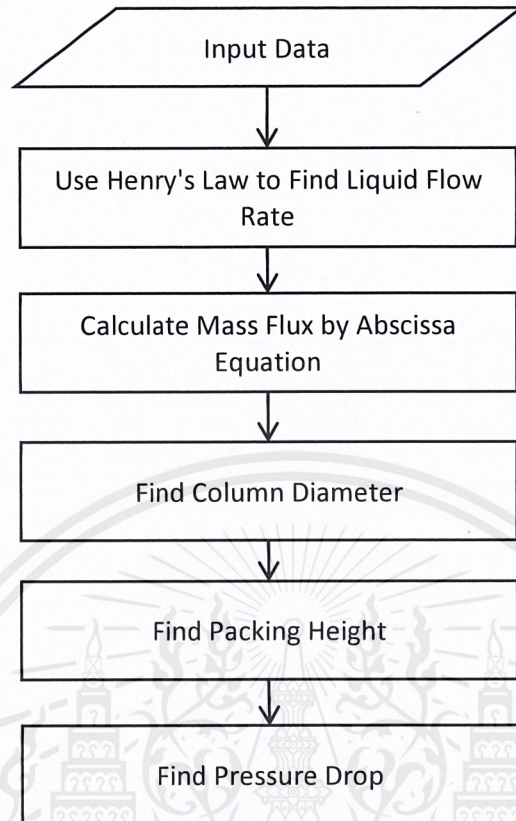


Figure 3.5 Calculation Flow Chart for Packed Bed Scrubber

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Mass Balance

Flow rate of stream lines are shown in Table 4.2. Mass balance for 1,030 ton/h of ammonium phosphate uses 72.1 ton/h of total phosphate, 27.6 ton/h of sulfuric acid and 2.84 ton/h of ammonia. The phosphoric acid process produce 29.3 ton/h of phosphoric acid as raw material in ammonium phosphate process. Ammonium phosphate, with 2 wt% of water content, contains 5 wt% of nitrogen and 39 wt% of phosphorous pentoxide. The summary of raw materials, products and utilities are shown in Table 4.1 and block flow diagram of fertilizer plant is shown in Figure 4.1.

Table 4.1 The Summary of Raw Materials, Products and Utilities in Fertilizer Plant

Phosphoric Acid Process	Raw Materials	Phosphate	55.1	ton/h
		Sulfuric Acid	25.5	ton/h
	Product	Phosphoric Acid	29.3	ton/h
	Utilities	Steam	28.6	ton/h
		Process Water	18.1	ton/h
		Cooling Water	3,037	m ³ /h
Ammonium Phosphate Process	Raw Materials	Phosphoric Acid	29.3	ton/h
		Phosphate	2.0	ton/h
		Sulfuric Acid	17.0	ton/h
		Ammonia	2.9	ton/h
	Product	Ammonium Phosphate	42.9	ton/h
	Utilities	Coating Agent	64	kg/h
		Natural Gas	840	kg/h

Some stream lines is neglected because it isn't affect to main process line. They are calculated in detail design steps. The combustion chamber burns natural gas with excess air (10 % excess).

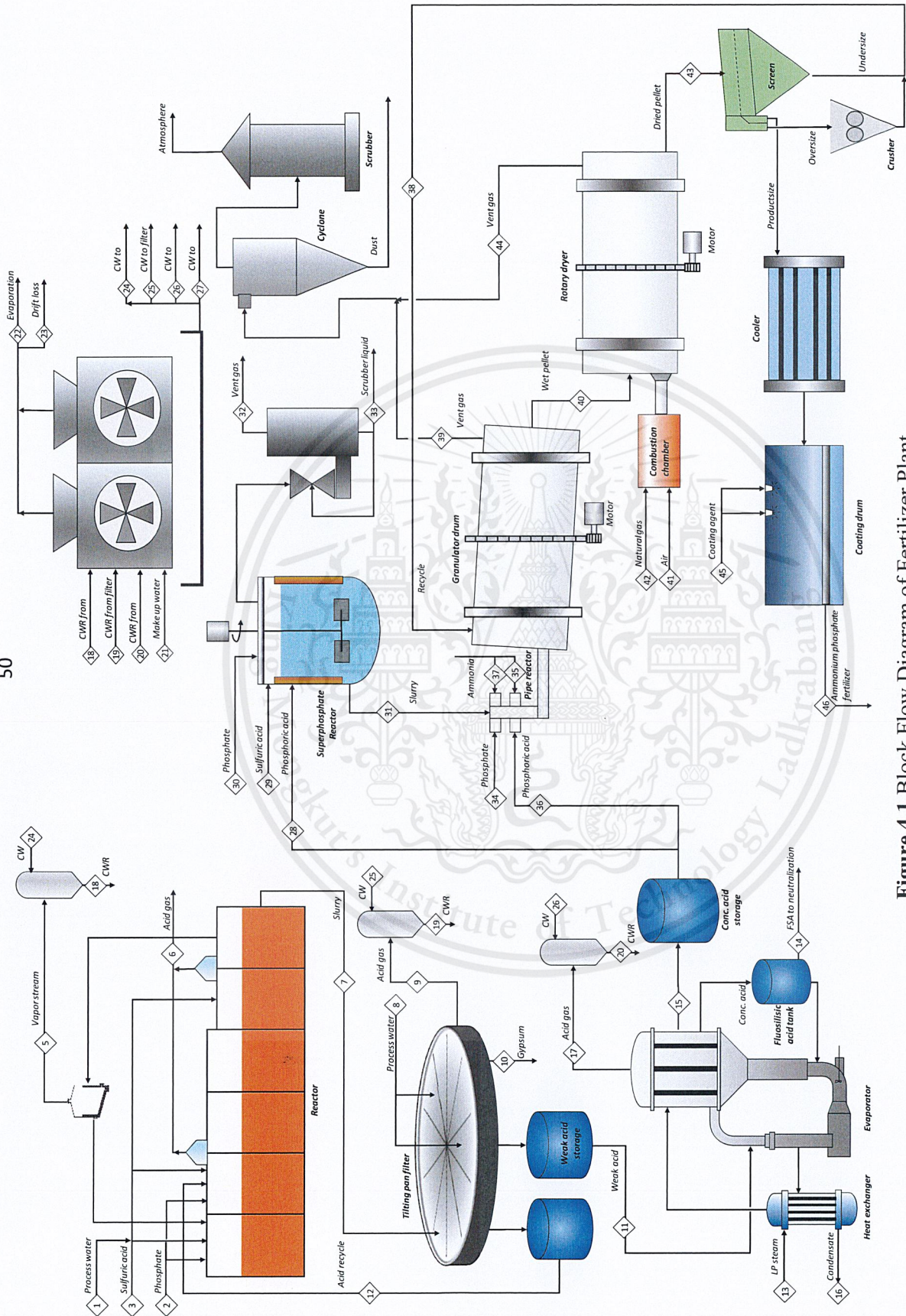


Figure 4.1 Block Flow Diagram of Fertilizer Plant

Table 4.2 Mass Balance of Fertilizer Plant

Streams No.	1	2	3	4	5	6	7	8	9	10
Name	Phosphate	Sulfuric Acid	Process Water	Recycle Acid	Vapor Stream	Acid Gas	Slurry to Filter	Process Water	Acid Gas	Gypsum
Flow rate (kg/h)	55,100	25,540	8,720	71,707	13,833	(detail design)	129,234	9,411	(detail design)	55,800

Streams No.	11	12	13	14	15	16	17	18	19	20
Name	Weak Acid	Recycle Acid	Steam	FAS to Neutralization	Conc. Acid	Condensate	Acid Gas	From Reactor	From Filter	From Evaporator
Flow rate (kg/h)	49,138	71,707	28,645	(detail design)	29,250	28,645	19,888	670*	478*	1,925*

Streams No.	21	22	23	24	25	26	27	28	29	30
Name	Make up	Evaporator Loss	Drift Loss	To Reactor	To Filter	To Evaporator	To Scrubber	Phosphate	Sulfuric Acid	Phosphoric Acid
Flow rate (kg/h)	34*	43*	6*	654*	473*	1,905*	25*	8,400	2,030	8,900

Streams No.	31	32	33	34	35	36	37	38	39	40
Name	Slurry to Granulator	Scrubber Liquid	Vent Gas to Stack	Phosphate	Ammonia	Phosphoric Acid	Ammonia	Recycle	Vent Gas	Pellet
Flow rate (kg/h)	19,330	(detail design)	(detail design)	8,600	1,460	21,230	1,390	128,570	(details design)	180,580

Streams No.	41	42	43	44	45	46
Name	Air	Natural Gas	Dry Pellet	Exhaust Gas	Coating Agent	Product
Flow rate (kg/h)	6,740	830	171,430	17,760	64	42,920

Note: * = m³/h

4.2 Rotary Dryer

Vendor's data sheet of combustion chamber uses heat around 13.40 MW. Heat consumption of dryer that is used to reduce product moisture content is 12.12 MW. The percent deviation of heat consumption is 9.55. Heat from calculation is less than vendor's calculation. Fertilizer must be less than 2 wt% moisture that is around 10.19 ton/h of water. Rotary dryer uses from combustion chamber that burns 840 kg/h of natural gas with 10% excess air. Combustion gas temperature is 250 °C. Product temperature increases from 50 to 93 °C. The combustion chamber data sheet is shown in Figure 4.2 and 4.3 to supply rotary dryer.

4.3 Cyclone

Cyclone has 2.21 m of diameter and 6.63 of total height that are used to collect 90% dust in air. Particle size that is higher than 5 μm can be collected in cyclone. Pressure drop of cyclone is 277 Pa that is used to design blower or fan. The pressure drop must be between 250-4000 Pa. If Pressure drop is out of range, input data must be verified. The calculation steps checks air velocity by using saltation velocity that is velocity to bring dust without fall and re-entrainment. The ratio is 0.85. The air velocity must be guessed between 8-30 m/s. Ratio of air velocity and saltation velocity must be less than 1.25 that is highest efficiency. The cyclone data sheet is shown in Figure 4.4 and 4.5. The vendor's diameter and height are 2.2 and 6.8, respectively. The percent deviation of diameter and height are 0.45 and 2.50, respectively.

4.4 Scrubber

Minimum liquid flow rate to absorb ammonia gas is 452.4 m^3/h , but operating liquid flow rate is 679 m^3/h for 1.5 times of minimum liquid flow rate. Column diameter is 5.38 m and packing height is 3.39 m. This packed bed scrubber uses plastic saddle intalox. Its packing factor is 131 m^{-1} . The data sheet is shown in Figure 4.6 and 4.7. The vendor's liquid flow rate, diameter and height are 479 m^3/h , 6 m and 3.8 m, but results have 5.64, 10.33 and 10.79 of percent deviation respectively.

**Combustion Chamber
Data Sheet**

		Combustion Chamber Data Sheet		
1	CUSTOMER Fertilizer plant	DATE		
2	LOCATION	AUTH. BY	CHKD. BY	MADE BY
3	UNIT			
4	SUPPLIER - JOB NO.			
5	ITEM NO. REQ. NO.	REV./DATE	LINE NO.	BY
6	SERVICE -			
7	NO. REQ'D Working 1 Stand by - Total 1			
8				
9	1. Function			
10	To provide hot air to dryer drum.			
11				
12	2. Combustion Chamber Design Information			
13	Type :	Natural gas burner		
14	Quantity :	Operate 1 unit, no standby		
15	Heat Duty :	12 MW		
16	Material :	CS Shell + Refractory Lining		
17	Pressure loss:	SBV		
18	Hot air temperature :	250-350 °C		
19	Hot gas flow rate :	SBV		
20	Turn down ratio :	SBV		
21	Noise Level :	< 85 dB at 1 m from Fan		
22	Safety :			
23	Ignition detection System :	SBV		
24	High Temperature Gas Detector :	SBV		
25				
26	3. Accessories			
27	3.1 Combustion Fan			
28	Type :	Centrifugal		
29	Flow rate :	SBV Nm ³ /hr		
30	Material (C/I) :	SBV		
31	Difference Pressure :	SBV mmH ₂ O		
32	3.2 Dilute Fan			
33	Type :	Centrifugal		
34	Flow rate :	SBV Nm ³ /hr		
35	Material (C/I) :	SBV		
36	Difference Pressure :	SBV mmH ₂ O		
37				
38				
39				
40				
41				
42				
43				

Figure 4.2 Combustion Chamber Data Sheet (1/2)

		DATA SHEET FOR CYCLONE				1/2																												
CUSTOMER: Phosphate Fertilizer Plant Project		REV	DATE	MADE BY	CHKD. BY	AUTH. BY																												
LOCATION:		A																																
UNIT: Cyclone		B																																
SUPPLIER	JOB NO.:	C																																
ITEM NO.:	REQ'N NO.	D																																
SERVICE: Cyclone		E																																
NO. REQ'D: (WORKING/ST ANDBY/TOTAL)		F																																
OPERATING CONDITIONS			SPECIFICATION																															
GAS		CYCLONE																																
- Composition : Air with AP Dust (Molecular Wt.)		- Type Centrifugal Cyclone																																
- Relative Humidity : 50 [%]		- Design Temp. 50 [°C]																																
- Density : - [kg/m ³]		- Design Press. 0 [kPaG]																																
- Temperature : Nor.: 20 Max.: 40 Des.: 50		- Test Press. <input type="checkbox"/> Hydrostatic [kPaG]																																
- Inlet Pressure : -7 [kPaG]		<input type="checkbox"/> Pneumatic [kPaG]																																
- Aallow. Pressure Drop : 2 [kPa]		- Corr. Allowance 1.6 for carbon steel [mm.]																																
- Solid Content :		- Shell Diameter 2,210 [mm.]																																
- Inlet : 4.2 [g-sol./Nm ³]		- Shell Height 6,630 [mm.]																																
- Outlet : 0.4 [g-sol./Nm ³]		- Shell thickness (1) [mm.]																																
SOLID		- Electrical Trace <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No																																
- Composition : AP (Ammonium Phosphate)		- Painting Refer project specification																																
- Temperature : Nor.: 23 Max.: 43 Des.: 50		- Insulation Yes (PP thickness 25 mm)																																
- Bulk Density : 900 [kg/m ³]		- Fire Proof N/A																																
- True Density : 1800 [kg/m ³]		<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>Mark</th> <th>Q'ty</th> <th>Size (mm.)</th> <th>Service</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>1</td> <td>(1)</td> <td>Inlet</td> </tr> <tr> <td>2</td> <td>1</td> <td>(1)</td> <td>Dust outlet (5)</td> </tr> <tr> <td>3</td> <td>1</td> <td>(1)</td> <td>Gas outlet</td> </tr> <tr> <td>4</td> <td>1</td> <td>(1)</td> <td>Handhole</td> </tr> <tr> <td>5</td> <td>1</td> <td>(1)</td> <td>Handhole w/retaining at dust chamber</td> </tr> <tr> <td>6</td> <td>1</td> <td>(1)</td> <td>Inspection hole at top</td> </tr> </tbody> </table>					Mark	Q'ty	Size (mm.)	Service	1	1	(1)	Inlet	2	1	(1)	Dust outlet (5)	3	1	(1)	Gas outlet	4	1	(1)	Handhole	5	1	(1)	Handhole w/retaining at dust chamber	6	1	(1)	Inspection hole at top
Mark	Q'ty	Size (mm.)	Service																															
1	1	(1)	Inlet																															
2	1	(1)	Dust outlet (5)																															
3	1	(1)	Gas outlet																															
4	1	(1)	Handhole																															
5	1	(1)	Handhole w/retaining at dust chamber																															
6	1	(1)	Inspection hole at top																															
- Angle of Repose : - [°]		NOZZLES & MANWAY																																
- Particle Size : 45 µm 50%																																		
Size [µm] [wt%]																																		
Distribution > 45 100																																		
45 µm under 0																																		
Total 100%																																		
- Water Content ≤ 2%Wt																																		
- Chemical <input checked="" type="checkbox"/> Corrosive Weak <input checked="" type="checkbox"/> Abrasive Weak		MATERIAL																																
Nature <input type="checkbox"/> Stringy <input type="checkbox"/> Dry		Shell / Cone Carbon Steel (1)																																
<input checked="" type="checkbox"/> Hygroscopic <input checked="" type="checkbox"/> Wet		Cover plate Carbon Steel (1)																																
<input checked="" type="checkbox"/> Non - freeflow <input type="checkbox"/> Greasy		Dust chamber Carbon Steel (1)																																
<input checked="" type="checkbox"/> Acidic <input type="checkbox"/> Lumpy material		Manholes / Nozzles Carbon Steel (1)																																
<input checked="" type="checkbox"/> Irregular <input type="checkbox"/> Uniform size		Support Carbon Steel (1)																																
<input type="checkbox"/> Interlocking material <input checked="" type="checkbox"/> Sticky		Bolt and Nuts Carbon Steel (1)																																
FLOW RATE (Nor.) - [Nm ³ /hr]		Gasket (1)																																
(Max.) 30,000 [Nm ³ /hr]		ACCESSORIES <input checked="" type="checkbox"/> Dust Chamber (1)																																
- Duration of Operation 24 [hr/day]		<input checked="" type="checkbox"/> Hand Holes (1)																																
LOCATION <input checked="" type="checkbox"/> Indoor <input type="checkbox"/> Outdoor		<input checked="" type="checkbox"/> Support Legs (1)																																
<input type="checkbox"/> Hazardous <input checked="" type="checkbox"/> Non - hazardous		<input checked="" type="checkbox"/> Insulation Support Lug																																
CODE & STANDARDS (1)		<input checked="" type="checkbox"/> Blind flanges with bolts/nuts/gaskets (1)																																
		<input checked="" type="checkbox"/> Foundation Bolts & Nuts (1)																																
		<input checked="" type="checkbox"/> Inspection Hole (1)																																
NET WEIGHT (1) [t / set]		<input checked="" type="checkbox"/> 2 Hitting Pads (1)																																
REMARKS																																		
1) By detail design																																		
2) By vendor																																		
3) Detail engineering to be confirmed																																		
4) <input checked="" type="checkbox"/> : to be applicable <input type="checkbox"/> : not to be applicable																																		
5) Double damper (about 0.5 ton) shall be hung by this nozzle-flange. Necessary rib shall be added to flange for reinforcement.																																		

Figure 4.4 Cyclone Data Sheet (1/2)

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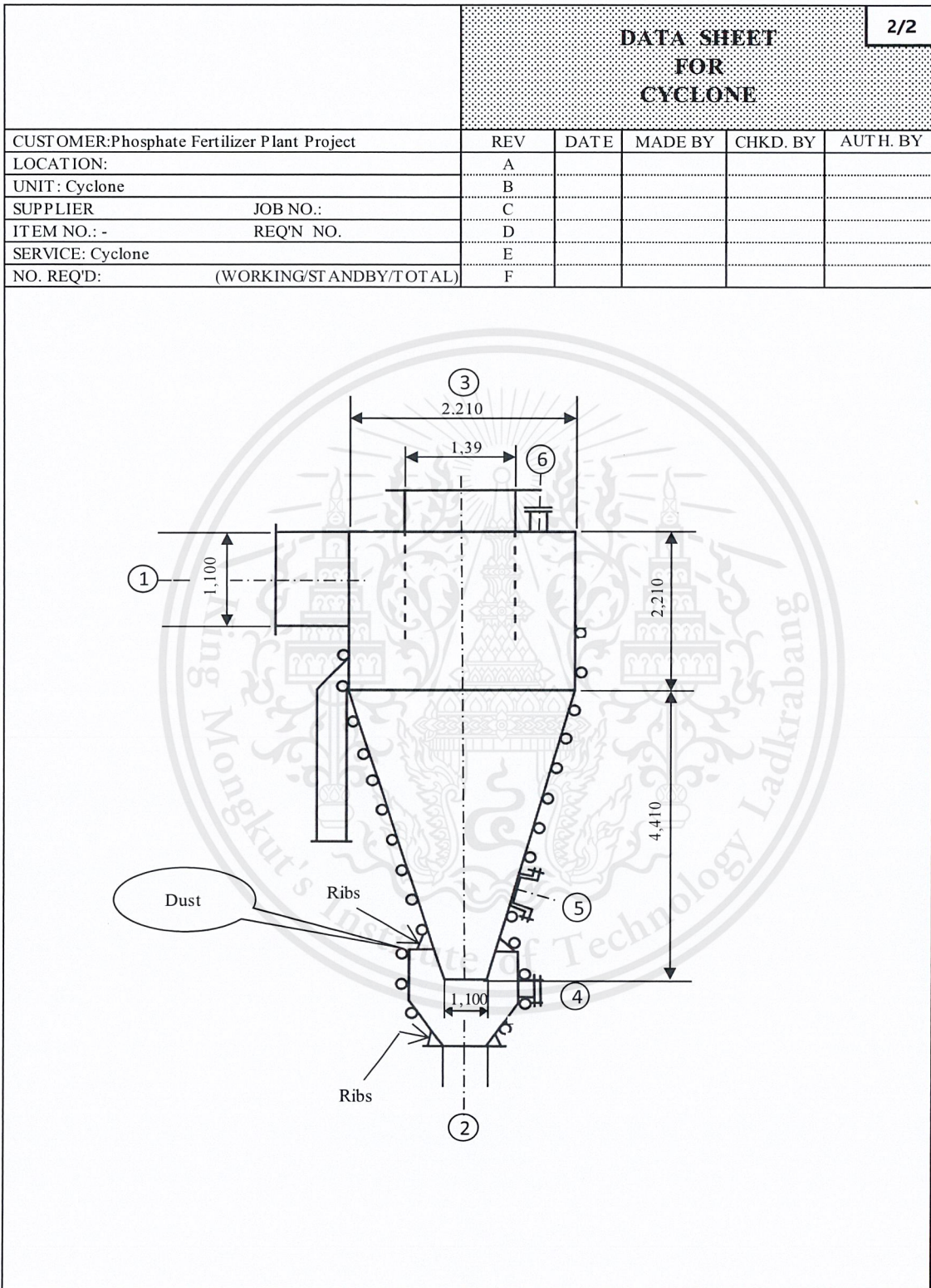


Figure 4.5 Cyclone Data Sheet (2/2)

							PACKED BED SCRUBBER DATA SHEET			
1	CUSTOMER						AUTHORIZED BY			
2	LOCATION						CHECKED BY			
3							REV.	DATE	MAED BY	
4	UNIT	Scrubber								
5	SUPPLIER	-	JOB NO.		-					
6	ITEM NO.	-	REQ. NO.		-					
7	SERVICE	-								
8	NO. REQ'D	Working	Unit	Stand-By	Unit	Total	Unit			
9	PROCESS CONDITIONS									
10	STREAM				INLET GAS					
11	Design Flow				290,000					
12	Normal flow				257,000-260,000					
13	Temperature				50-60					
14	Density				1					
15	Relative Pressure				+2.25					
16	Relative humidity				50					
17	Normal / max ammonia				100 - 300 / 350					
18										
19	STREAM				OUTLET GAS					
20	Design Flow				285,000					
21	Normal flow				249,000-253,000					
22	Temperature				40-50					
23	Density				1					
24	Relative Pressure				+0.75					
25	Relative humidity				100					
26	Normal / max ammonia				24-28 /40					
27										
28	SCRUBBER LIQUID				Tower					
29	Design Flow				680					
30	Normal flow				452					
31	Temperature				50					
32	Density				990-1,020					
33	Solid				2.5 max.					
34										
35	MATERIALS									
36	Venturi				-					
37	Horiz. Arm				RLCS//FRP					
38	Tower				RLCS//FRP					
39	Cone				-					
40	Internals				Intalox saddle PP					
41	Gasgets				-					
42										
43	PRESSURE DROP									
44	Preessure Drop				1					
45					kPa					
46										

Figure 4.6 Scrubber Data Sheet (1/2)

							PACKED BED SCRUBBER DATA SHEET		
1	CUSTOMER						AUTHORIZED BY		
2	LOCATION						CHECKED BY		
3							REV.	DATE	MAED BY
4	UNIT	Scrubber							
5	SUPPLIER	-	JOB NO.		-				
6	ITEM NO.	-	REQ. NO.		-				
7	SERVICE	-							
8	NO. REQ'D	Working	Unit	Stand-By	Unit	Total	Unit		
9									
10	EMISSION								
11	F	Maximum 5					mg/Nm ³		
12	NH ₃	Maximum 50					mg/Nm ³		
13	Dust	Maximum 50					mg/Nm ³		
14	SO ₂	Maximum 10					mg/Nm ³		
15	NOx	Maximum 20					mg/Nm ³		
16	Temperature	50-70					°C		
17									
18	COLUMN								
19	Diameter	5.38					m		
20	Packed height	3.39					m		
21									
22	Notes:								
23	Minimum efficiency required: Ammonia 95% Dust 95%								
24	Outlet gas goes to stack								
25									
26									
27									
28									
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46									

Figure 4.7 Scrubber Data Sheet

The comparison of results are show in Table 4.3. The results are compared with vendor's data sheet. Mostly results are less than vendor's specification.

Table 4.3 The Percent Deviation of Results

	Templates	References	Percent Deviation
Mass Balance			
Ammonium Phosphate Product (ton/day)	1,030.00	1,000.00	3.00
Rotary Dryer			
Heat Duty (MW)	12.12	13.40	9.55
Cyclone			
Diameter (m)	2.21	2.20	0.45
Height (m)	6.63	6.80	2.50
Packed Bed Scrubber			
Liquid Flow Rate (m ³ /h)	452.00	479.00	5.64
Column Diameter (m)	5.38	6.00	10.33
Packing Height (m)	3.39	3.80	10.79

CHAPTER V

CONCLUSION

The calculation results are shown in Table 5.1. Ammonium phosphate from mass balance calculation is 1,030 ton/d. Heat duty of the rotary dryer is 12.12 MW. Cyclone diameter and height are 2.21 and 6.63 m, respectively. The flow rate of water in packed bed scrubber for ammonia absorption is 452 m³/h. The column diameter of packed bed scrubber and packing height are 5.38 and 3.39 m, respectively. Each calculation result is less than 11 percent deviation. The calculation data sheets can be used for preliminary equipment design in acceptable ranges.

Table 5.1 Results of Mass Balances, Rotary Dryer, Cyclone and Packed Bed Scrubber

Results	
Mass Balance	
Ammonium Phosphate Product (ton/day)	1,030.00
Rotary Dryer	
Heat Duty (MW)	12.12
Cyclone	
Diameter (m)	2.21
Height (m)	6.63
Packed Bed Scrubber	
Water Flow Rate (m ³ /h)	452.00
Column Diameter (m)	5.38
Packing Height (m)	3.39

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Appendix A

Raw Data

Appendix A summarizes total raw data that are used to calculate in this project. Raw data are classified in 4 part. Most of raw data are come from vendor's data sheet of each equipment and properties from references.

1. Mass Balance Calculation

The properties of raw materials are show in Table A-1. The acid concentrations are shown in Table A-3. The properties of components in fertilizer plant are shown in Table A-2.

Table A-1 Raw Materials of Fertilizer Plant

Raw Material	Total Feed (TPH)	
Phosphate	Phosphoric Acid Reactor	55.10
	TSP/SSP Reactor	8.40
	Granulator	8.60
	Total	72.10

Table A-2 Properties of Components in Fertilizer Plant

Compound	Mw (kg/mol)	Cp (kJ/kg.K)	Heat of Vap. (kJ/kg)
$\text{Ca}_3(\text{PO}_4)_2$	0.310	-	-
H_2SO_4	0.098	-	-
H_2O	0.018	4.20	2257
$\text{Ca}_3\text{SO}_4 \cdot 2\text{H}_2\text{O}$	0.172	-	-
H_3PO_4	0.098	-	-
P_2O_5	0.142	-	-
$\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$	0.250	-	-
DAP	0.132	1.42	-
Air	0.029	1.01	-
Methane	0.016	2.29	-
CaSO_4	0.136	-	-
$\text{Ca}(\text{H}_2\text{PO}_4)_2$	0.232	-	-

Table A-3 The Concentration of Raw Materials

Raw Material	Concentration
Phosphate	24.5 wt% of P ₂ O ₅
Sulfuric acid	99.6 wt%
Ammonia	99.6 wt%
Natural Gas	93.4 wt% of Methane

Heat of reaction of phosphoric acid, TSP and SSP are 375.53, 722.07 and 453.71 kJ/mol respectively. Phosphoric acid process operates 23 h, but ammonium phosphate operates 24 h.

2. Dryer Calculation

The constant values for heat capacity calculation is shown in Table A-4. Parameters from vendor's data sheet is illustrated in Table A-5. The natural gas composition that is used in fertilizer plant is shown in Table A-6.

Table A-4 Constant Value of Heat Capacity Equation

	A	B (10 ⁻³)	C (10 ⁻⁶)	D (10 ⁵)
Air	3.355	0.575	-	-0.016
Steam	3.470	1.450	-	0.121
Water	8.721	1.250	-0.180	-

Table A-5 Parameters of Rotary Dryer Calculation

Parameters	Values
Feed Solid (kg/h)	180000
Moisture Content in Feed	8.00%
Moisture Content in Product	2.00%
Humidity (kg water/kg dry air)	0.01
Feed Temperature (°C)	50
Product Temperature (°C)	93
Inlet Air Temperature (°C)	250
Relative Humidity	50%

Table A-6 Component of Natural Gas

Components	wt%
Methane	93.39
Ethane	4.40
Propane	0.40
Iso - Butane	0.14
normal - Butane	0.10
Iso - Pentane	0.03
Normal - Pentane	0.01
Hexanes plus	0.01
Nitrogen	1.00
Carbon Dioxide	0.50
Oxygen	0.02
Hydrogen	trace

3. Cyclone Calculation

The parameters for cyclone calculation and pressure drop calculation are shown in Table A-7 and A-10 respectively. Inlet gas properties are illustrated in Table A-8. Table A-9 shows particle size that comes from vendor's data sheet.

Table A-7 Parameters of Cyclone Calculation

Parameters	Values
Air Flow Rate per Cyclone (m^3/s)	8.33
Particle Density (kg/m^3)	900.00
Inlet Temperature ($^{\circ}\text{C}$)	50.00
Inlet Pressure (kPa)	101.30
Inlet Dust Concentration (g/m^3)	35.00
Outlet Dust Concentration (g/m^3)	3.50

Table A-8 Parameters of Inlet Gas Properties

Inlet Gas	Air
Molecular Weight of Inlet Gas (g/mole)	28.96
Density (kg/m ³)	1.09
Viscosity (cP)	0.0195

Table A-9 Particle Size Distribution

Mesh	Diameter (μm)	Weight Fraction
60	245.20	0.058
80	183.66	0.093
125	117.30	0.08
200	73.16	0.059
287.5	50.81	0.053
325	44.92	0.657

Table A-10 Parameters for Pressure Drop Calculation

Parameters	Values
Vessel Velocity (m/s)	13
Vessel Area (m ²)	1.32
Velocity of Particle Inlet (m/s)	-
Velocity of Particle in Vessel (m/s)	-
Velocity of exit Gas (m/s)	13.71
Velocity in Cyclone (m/s)	13

4. Packed bed Scrubber Calculation

Parameter for packed bed scrubber calculation is shown in Table A-11. Henry's constant and mass transfer coefficient are illustrated in Table A-12 and A-13 respectively.

Table A-11 Parameters for Packed Bed Scrubber Calculation

Parameters	Values
Column operating pressure (atm)	101.30
Temperature (°C)	50.00
Target efficiency	95%
Primary component	Air
Flow rate (m ³ /h)	290,000
Molecular weight (g/mol)	28.96
Density (kg/m ³)	1.00
Solute component	NH ₃
Molecular weight (g/mol)	17.00
Density (kg/m ³)	1,005
Concentration (mg/m ³)	350.00

Table A-12 Henry's Constant

Substance	KH	DeltaH/R
NH ₃ , ammonia	0.937	4100
HBr, hydrogen bromide	77.9	6100
HCl, hydrogen chloride	0.03	0
H ₂ S, hydrogen sulfide	553	2100
SO ₂ , sulfur dioxide	46.1	3100
C ₂ H ₅ OH, ethanol	0.3	6500
CH ₃ COOH, acetic acid	0.011	6300
CH ₃ COCH ₃ , acetone	1.95	4600
C ₃ H ₃ N, acrylonitrile	5	2800
Cl ₂ , chlorine	608	2500
HCHO, formaldehyde	0.017	6800

Table A-13 Mass Transfer Coefficient

Solute Gas	Absorbent Liquid	K_{GA} (lb mol/h ft ³ atm)
Br ₂	5% NaOH	5.00
Cl ₂	Water	4.60
Cl ₂	8% NaOH	14.00
CO ₂	4% NaOH	2.00
HBr	Water	5.90
HCHO	Water	5.90
HCl	Water	19.00
HCN	Water	5.90
HF	Water	8.00
H ₂ S	4% NaOH	5.90
NH ₃	Water	17.00
SO ₂	Water	3.00
SO ₂	11% Na ₂ CO ₃	12.00

Appendix B

Mass Balance Calculation

Example of calculation

1. Phosphoric Acid Reactor

Phosphate feed to reactor is 55.1 ton/h that consist of 24.5 wt% of P₂O₅. The reaction following Equation 2.1 that is



This reaction has 0.91 conversion based on licensor. Calcium phosphate in phosphate feed that is reacted in reactor is 26,818 kg/h

$$\text{Calcium phosphate} = \frac{55,100 \text{ kg/h} \times 0.245 \times 0.310 \text{ kg/mol} \times 0.91}{0.142 \text{ kg/mol}} = 26,818 \frac{\text{kg}}{\text{h}} \text{ or } 86,510 \frac{\text{mol}}{\text{h}}$$

Sulfuric acid, water, phosphoric acid and gypsum are shown in Table A-1.

Table B-1 The Mass Balance of Wet Process Reaction

Chemicals	Mole Flow Rate (mol/h)	Mass Flow Rate (kg/h)
Calcium phosphate	86,510	26,818
Sulfuric acid	259,532	25,434
water	519,065	9,340
phosphoric acid	173,021	16,956
gypsum	259,532	44,640

2. Tilting pan Filter

Filter is used to separate gypsum and phosphoric acid. Phosphoric acid has 25 wt% of P₂O₅ and gypsum has 80 wt% of water. Gypsum and phosphoric acid are 223,200 and 48,770 kg/h respectively.

3. Evaporator

Evaporator increase concentration of acid from 25 to 42 wt% of P₂O₅.

$$\text{Concentrated acid} = \frac{48,770 \text{ kg/h} \times 0.25}{0.42} = 29,249 \frac{\text{kg}}{\text{h}}$$

4. Acidic Cooling Tower

The stream lines from reactor condenser, filter condenser and evaporator condenser have total feed at 41 m³/h. Cooling water to remove heat in reactor is 654 m³/h. Cooling water to filter condenser and evaporator condenser are 473 and 1,905 m³/h.

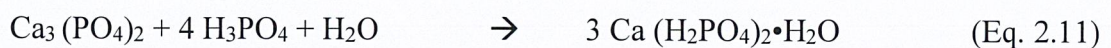
$$\begin{aligned} Q_{\text{reactor}} &= \frac{\frac{16 \text{ m}^3}{\text{h}} \times \frac{998 \text{ kg}}{\text{h}}}{\frac{2257 \text{ kJ}}{\text{kg}}} \\ &= 7.58 \text{ MW} \\ \text{Cooling Water} &= \frac{Q_{\text{reactor}}}{C_p \times \Delta T \times \text{Density}} \\ &= \frac{Q_{\text{reactor}}}{4.184 \frac{\text{kJ}}{\text{kg K}} \times 10 \text{ K} \times 998 \text{ kg/h}} \\ &= 654 \text{ m}^3/\text{h} \end{aligned}$$

Cooling water calculation is repeat of filter condenser and evaporator condenser.

5. Super Phosphate Reactor

This reactor has additional phosphate feed at 8.4 ton/h that is fed to TSP and SSP at 4.2 ton/h at 24.5 wt% of P₂O₅. The reactions is following Equation 2.11 and 2.12.

Tri Superphosphate (TSP)



Single superphosphate (SSP)



Table B-2 Summary of the Reactor Calculation

Chemicals	Mole Flow Rate (mol/h)	Mass Flow Rate (kg/h)
Calcium Phosphate	14,494	4,492
Phosphoric Acid	28,989	2,841
Sulfuric Acid	14,494	1,420
Water	28,989	521
Mono calcium phosphate	28,989	7,247
Calcium sulphate	14,494	1,971

In feed phosphoric has 42 wt% of P₂O₅.

$$\text{Phosphoric Acid Feed} = \frac{2,841 \text{ kg/h} \times 0.142 \text{ kg/mol}}{0.098 \text{ kg/mol} \times 2 \times 0.42} = 4,900 \frac{\text{kg}}{\text{h}}$$

and sulfuric acid has 99.60 wt% that is 1,426 kg/h

6. Granulator

Granulator mix slurry with additional phosphoric acid, phosphate and ammonia to produce ammonium phosphate that contain of 5 wt% of nitrogen and 39 wt% of P₂O₅. The ratio of P₂O₅ per N is 7.8. In addition, 8.6 ton/h of phosphate and 3.12 ton/h of ammonia are fed to granulator. Other phosphoric acid is fed to granulator at 25.41 ton/h. Ammonia has 99.60 wt%. The recycle pellet from screen is 124,940 kg/h.

$$\begin{aligned} \text{Feed P}_2\text{O}_5 &= \left(\frac{8,600 \text{ kg}}{\text{h}} + \frac{8,400 \text{ kg}}{\text{h}} \right) \times 0.245 + \left(\frac{4,900 \text{ kg}}{\text{h}} + \frac{25,410 \text{ kg}}{\text{h}} \right) \times 0.42 \\ &= 16,516 \frac{\text{kg}}{\text{h}} \end{aligned}$$

$$\begin{aligned} \text{Nitrogen} &= \frac{16,516 \text{ kg}}{7.8} \\ &= 2,559 \frac{\text{kg}}{\text{h}} \end{aligned}$$

$$\begin{aligned} \text{Ammonia} &= \frac{\frac{2,559 \text{ kg}}{\text{h}} \times \frac{0.017 \text{ kg}}{\text{mol}}}{\frac{0.014 \text{ kg}}{\text{mol}} \times 0.996} \\ &= 3,120 \frac{\text{kg}}{\text{h}} \end{aligned}$$

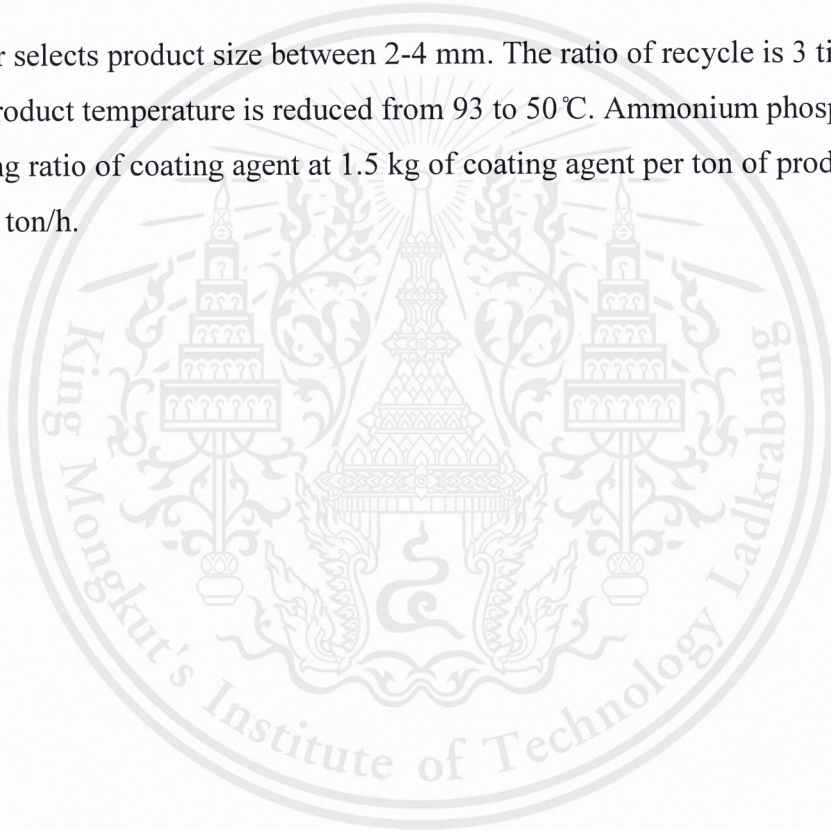
7. Rotary Dryer

Rotary dryer reduce moisture content from 8.68 wt% to 2 wt%. Total feed of dryer is 177,400 kg/h.

$$\begin{aligned} \text{Water removal} &= \frac{177,400\text{kg}}{h} \times 8.68 - \frac{177,400\text{kg}}{h} \times 2.00 \\ &= 11,855 \frac{\text{kg}}{h} \end{aligned}$$

8. Screener, Cooler and Coating Drum

Screener selects product size between 2-4 mm. The ratio of recycle is 3 times that is 124,940 kg/h. Product temperature is reduced from 93 to 50 °C. Ammonium phosphate product is coated by using ratio of coating agent at 1.5 kg of coating agent per ton of product. The product is 42.92 ton/h.



Appendix C

Dryer Calculation

Heat Capacity Calculation

Heat capacities of water, steam and air are calculated with ideal gas assumption.

$$\frac{C_p}{R} = A + BT + CT^2 + DT^{-2} \quad (C-1)$$

Example of Heat Capacity Calculation (Water at 50 °C)

The constant values in equation C-1 are shown in Table C-1.

Table C-1 Constant Values for Heat Capacity [J.M. smith, H.C. van ness and M.M. abbot, 2015]

	A	B (10 ⁻³)	C (10 ⁻⁶)	D (10 ⁵)
Air	3.355	0.575	-	-0.016
Steam	3.470	1.450	-	0.121
Water	8.721	1.250	-0.180	-

$$C_{p,water} = (3.355 + 0.575 \times 10^{-3}(323) - 0.016 \times 10^5(323)^{-2}) \times 8.314 = 4.27 \frac{kJ}{kg K}$$

The heat capacities of steam and air are 1.95 and 1.05 kJ/kg K, respectively.

Wet Bulb temperature Calculation

Relative humidity is 50% and station pressure is 101.3 kPa.

$$\text{Saturated Vapor Pressure} = 6.112 \times e^{(17.67 \times 250)/(250 + 243.5)} = 47,175 Pa$$

$$\text{Vapor Pressure} = \frac{47,175 \times 50\%}{100} = 23,588 Pa$$

Guessed wet bulb temperature is 214 °C

Saturated Vapor Pressure at Wet Bulb Temperature

$$= 6.112 \times e^{(17.67 \times 214)/(214 + 243.5)} = 23,620 Pa$$

Calculation Vapor Pressure

$$= 23,620 - 101.3 \times (250 - 214) \times 0.00066 \times (1 + (0.00115 \times 214)) = 23,588 \text{ Pa}$$

$$\text{Different Vapor Pressure} = 23,588 - 23,588 = 0 \text{ Pa}$$

Different vapor pressure is very less. This wet bulb temperature is true.

Outlet Air temperature Calculation

Number of transfer unit is defined at 2.5 to calculate outlet air temperature.

$$2.5 = \ln \frac{T_{hb} - 214}{250 - 214}; \text{ Outlet Air Temperature} = 217^\circ\text{C}$$

Heat Consumption Calculation

$$\frac{q_T}{18,000} = 1.42 \times (93 - 50) + 8.68\% \times 4.27 \times (214 - 50) + 6.68\% \times 2257 + 2\% \times (93 - 214) + 6.68\% \times 1.95(217 - 213)$$

$$\text{Heat Consumption} = 12.12 \text{ MW}$$

Appendix D

Cyclone Calculation

Cyclone Geometry Calculation

The cyclone geometry is following cyclone model. Air velocity is used to find inlet area that is use to convert to others size. The models are shown in Table 3.1

Table 3.1 Cyclone configuration models.

Term	Description	Stairmand	Swift	Lapple	Parnell
H_c/D_c	Inlet height	0.50	0.44	0.50	0.50
B_c/D_c	Inlet width	0.20	0.21	0.25	0.25
S_c/D_c	Outlet length	0.00	0.06	0.13	0.13
D_e/D_c	Outlet diameter	0.50	0.40	0.50	0.63
L_c/D_c	Cylinder height	1.50	1.40	2.00	1.00
Z_c/D_c	Overall height	3.00	2.50	2.00	2.00
J_c/D_c	Dust outlet	0.38	0.40	0.25	0.50

Air velocity is guessed at 13.71 m/s. The volumetric flow rate is divided by air velocity to find inlet area. The model that is selected is Parnell.

$$H_c \times B_c = \frac{q}{v_i} = \frac{8.33 \text{ m}^3/\text{s}}{13.71 \text{ m/s}} = 0.61 \text{ m}^2$$

$$H_c = 0.5 \times D_c; B_c = 0.25 \times D_c$$

$$D_c = \left(\frac{0.61 \text{ m}^2}{0.5 \times 0.25} \right)^{-2} = 2.21 \text{ m}$$

The sizing of cyclone is used diameter to convert in others part. The summary of cyclone sizing is shown in Table D-1.

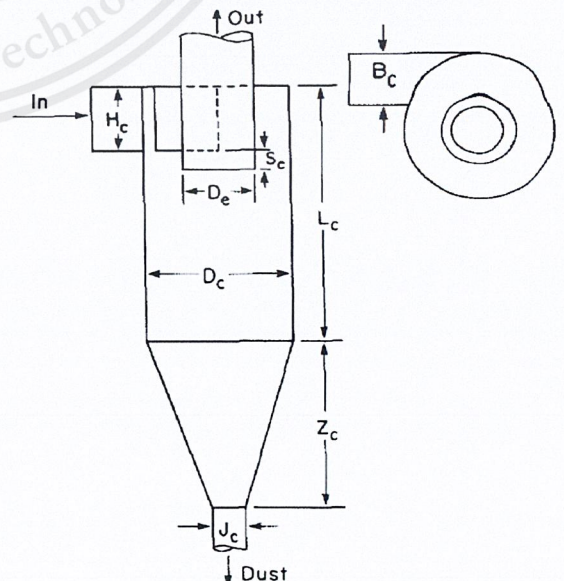


Figure D-1 Cyclone Geometry

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$$H_C = 0.5 \times D_C = 0.5 \times 2.21 = 1.11 \text{ m}$$

$$B_C = 0.25 \times D_C = 0.25 \times 2.21 = 0.56 \text{ m}$$

$$S_C = 0.13 \times D_C = 0.13 \times 2.21 = 0.29 \text{ m}$$

$$D_e = 0.63 \times D_C = 0.63 \times 2.21 = 1.39 \text{ m}$$

$$L_C = 1.0 \times D_C = 1.0 \times 2.21 = 2.21 \text{ m}$$

$$Z_C = 2.0 \times D_C = 2.0 \times 2.21 = 4.42 \text{ m}$$

$$J_C = 5.0 \times D_C = 5.0 \times 2.21 = 1.11 \text{ m}$$

Table D-1 Cyclone Geometry in Case Study

Description	Sizing (m)
Inlet height	1.11
Inlet width	0.56
Outlet length	0.29
Outlet diameter	1.39
Cylinder height	2.21
Overall height	4.42
Dust outlet	1.11

Cutting Diameter Calculation

The cutting diameter is used to calculate collection efficiency that is equation 3.11. The cutting diameter is 17.68 μm . This particle is size that has 50% collection efficiency. Each particle size has one efficiency that is summarized to collect total efficiency.

$$\begin{aligned}
 d_{pc} &= \left(\frac{9\mu W}{2\pi N_s v_i (\rho_p - \rho_g)} \right)^{0.5} & (3.11) \\
 &= \left(\frac{9(0.0196cP)0.56m}{2\pi 4 \times \frac{13.71m}{s} (900-1.1) \frac{kg}{m^3}} \right)^{0.5} \\
 &= 17.68\mu\text{m}
 \end{aligned}$$

Collection Efficiency Calculation

The efficiency is used to compare with target efficiency. The collection efficiency is calculate with equation 3.12. The particle size of dust are shown in Table D-2.

Table D-2 Particle Size of Dust in Inlet Gas Stream

Diameter (μm)	Weight Fraction
245.20	0.058
183.66	0.093
117.30	0.08
73.16	0.059
50.81	0.053
44.92	0.657

$$\eta = \frac{1}{1 + \left(\frac{d_{pc}}{d_{pj}}\right)^2} \quad (3.12)$$

$$= \frac{1}{1 + \left(\frac{245.20\mu\text{m}}{17.68\mu\text{m}}\right)^2}$$

$$= 0.9948$$

The collection efficiency of each particle sizes are shown in Table D-3. Total collection efficiency is 0.899 that is nearly with target efficiency at 0.9. The percent deviation of efficiency is less than 1%. If percent collection efficiency is higher than 3%, the air velocity is guessed a one more. When air velocity is guessed a new value, the step of calculation is repeated.

Table D-3 Collection Efficiency of Each Particle Size

Diameter (μm)	Weight Fraction	Collection Efficiency
245.20	0.06	0.9948
183.66	0.09	0.9908
117.30	0.08	0.9778
73.16	0.06	0.9448
50.81	0.05	0.8920
44.92	0.66	0.8658

Saltation Velocity Calculation

The saltation velocity is a velocity to convey dust in air to cyclone. This velocity is used to verify air velocity. The equation are show in equation 3.13.

$$\omega = \left(\frac{4g\mu(\rho_p - \rho_f)}{3\rho_f^2} \right)^{\frac{1}{3}} \quad (D-1)$$

$$= \left(\frac{4 \left(\frac{32.2 ft}{s^2} \right) 0.019 cP (56.19 - 0.068) lb/ft^3}{3(0.068 lb/ft^3)^2} \right)^{\frac{1}{3}}$$

$$= 1.89$$

$$v_s = 2.055 \omega \left(\frac{(W/D)^{0.4}}{(1-W/D)^{0.333}} \right) D^{0.667} v_i^{0.667} \quad (3.13)$$

$$= 2.055(1.89) \left(\frac{(0.56m/2.21m)^{0.4}}{(1 - 0.56m/2.21m)^{0.333}} \right) 2.21m^{0.667} 13.71^{0.667}$$

$$= 116.64 \frac{ft}{s} = 33.55 \frac{m}{s}$$

The ratio of air velocity and saltation velocity is 13.71/33.55 or 0.39 that less than 1.25. This air velocity can be used and the air velocity best be between 8-30 m/s. If this ratio is higher than 1.2, the dust is spread in air.

Pressure Drop Calculation

The pressure drop consist of 5 terms that are show in equation 3.14 - 3.20.

1. Pressure drop of inlet contraction

$$A = \frac{W_C \times H_C}{A_C} \quad (A-2)$$

$$= \frac{0.55 \times 1.1}{1.32}$$

$$= 0.417$$

$$K = -12.5 \times A^4 + 10 \times A^3 - 2.625 \times A^2 - 0.125 \times A + 0.5 \quad (\text{A-3})$$

$$\begin{aligned} &= -12.5 \times 0.417^4 + 10 \times 0.417^3 - 2.625 \times 0.417^2 - 0.125 \times 0.417 + 0.5 \\ &= 0.46 \end{aligned}$$

$$\Delta P_i = 0.5 \rho_g (v_{in}^2 - v_{vessel}^2 + K v_{in}^2) \quad (3.14)$$

$$= \frac{0.51.1kg}{m^3 \left(\left(\frac{13.71m}{s} \right)^2 - \left(\frac{13m}{s} \right)^2 + 0.3 \left(\frac{13.71m}{s} \right)^2 \right)}$$

$$= 41 Pa$$

2. Pressure drop of particle acceleration

This term is neglect because the particle density is unknown.

3. Pressure drop of barrel friction

$$Re = \frac{\rho_g D_c v_g}{\mu_g} \quad (3.18)$$

$$= \frac{1.1kg/m^3 (2.21m) 13.71m/s}{0.0195 cP}$$

$$= 4.22 \times 10^5$$

$$f = 0.25 \left(\log \left(\frac{e/D}{3.7} + \frac{5.74}{Re^{0.9}} \right) \right)^{-2} \quad (3.17)$$

$$= 0.25 \left(\log \left(\frac{0.000254m/2.21m}{3.7} + \frac{5.74}{(4.22 \times 10^5)^{0.9}} \right) \right)^{-2}$$

$$= 0.129$$

$$d_{in} = 2(H_C \times B_C)(H_C + B_C) \quad (\text{A-5})$$

$$= 2(1.11 \times 0.55)(1.11 + 0.55)$$

$$= 2.03 m$$

$$\Delta P_b = \frac{2f \rho_g v_{in}^2 \pi D_c N_s}{d_{in}} \quad (3.16)$$

$$= \frac{2(0.129)1.1kg/m^3 (13.71m/s)^2 \pi 2.21m(4)}{2.03 m}$$

$$= 73.21 \text{ Pa}$$

4. Pressure drop of gas flow reversal

$$\Delta P_g = \frac{\rho_g v_{in}^2}{2} \quad (3.19)$$

$$= \frac{(1.1 \text{ kg/m}^3)(13.71 \text{ m/s})^2}{2}$$

$$= 102.59 \text{ Pa}$$

5. Pressure drop of exit contraction

$$\Delta P_e = 0.5 \rho_g (v_{exit}^2 - v_c^2 + K v_{exit}^2) \quad (3.20)$$

$$= 0.5(1.1 \text{ kg/m}^3)((13 \text{ m/s})^2 - (13.71 \text{ m/s})^2 + 0.46 (13.71 \text{ m/s})^2)$$

$$= 59.73 \text{ Pa}$$

The total pressure drop must be between 250-4000 Pa that is 277 Pa. If pressure drop is high, dust is hard to separate. The cyclone is small at high pressure drop.

Appendix E

Packed Bed Scrubber Calculation

Liquid Flow rate Calculation

Mole fraction of inlet liquid that has not ammonia component is zero. Mole fraction of outlet air is fixed at 0.0032. Mole fraction of liquid and air are plotted and drag line to equilibrium line at mole fraction of inlet air. Equilibrium line at low concentration uses Henry's law to estimate. Henry's constant is 2.71 atm.

$$y_2 = \frac{\dot{m}_{NH_3}/M_{WNH_3}}{V_{air} \times \frac{\rho_{air}}{M_{wair}} + \dot{m}_{NH_3}/M_{WNH_3}} \quad (E-1)$$

$$= \frac{\frac{17.5mg}{17g}}{\frac{1kg}{m^3} \times \frac{m^3}{29g} + \frac{17.5mg}{17g}} \\ = 0.0032$$

$$y_1 = \frac{\dot{m}_{NH_3}/M_{WNH_3}}{V_{air} \times \frac{\rho_{air}}{M_{wair}} + \dot{m}_{NH_3}/M_{WNH_3}} \quad (E-2)$$

$$= \frac{350}{\frac{1kg}{m^3} \times \frac{m^3}{29g} + \frac{350mg}{17g}} \\ = 0.0596$$

Mole fraction of outlet liquid is 0.0147 at minimum liquid flow rate that is shown in Figure E-1. Minimum liquid flow rate is 452.4 m³/h. Operating liquid flow rate that is 1.5 times of minimum liquid flow rate is 679 m³/h.

$$Inlet\ air = V_{air} \times \frac{\rho_{air}}{M_{wair}} \quad (E-3)$$

$$= 290,000m^3/h \times \frac{1kg/m^3}{29g/mole}$$

$$= 9.42 \times 10^6 mol/h$$

$$L' \left(\frac{x_0}{1-x_0} \right) + V' \left(\frac{y_2}{1-y_2} \right) = L' \left(\frac{x_1}{1-x_1} \right) + V' \left(\frac{y_1}{1-y_1} \right) \quad (3.21)$$

$$L' \left(\frac{0.0147}{1-0.0147} \right) + 9.42 \times \frac{10^6 \text{ mol}}{\text{hm}} \left(\frac{0.0032}{1-0.0032} \right) = L' \left(\frac{0}{1-0} \right) + 9.42 \times \frac{10^6 \text{ mol}}{\text{h}} \left(\frac{0.0596}{1-0.0596} \right)$$

$$L' = 2.53 \times 10^7 \text{ mole/h}$$

$$= 452 \text{ m}^3/\text{h}$$

$$L'_{\text{Operating}} = 1.5 \times L' \quad (E-4)$$

$$= 1.5 \times 452 \text{ m}^3/\text{h}$$

$$= 679 \text{ m}^3/\text{h}$$

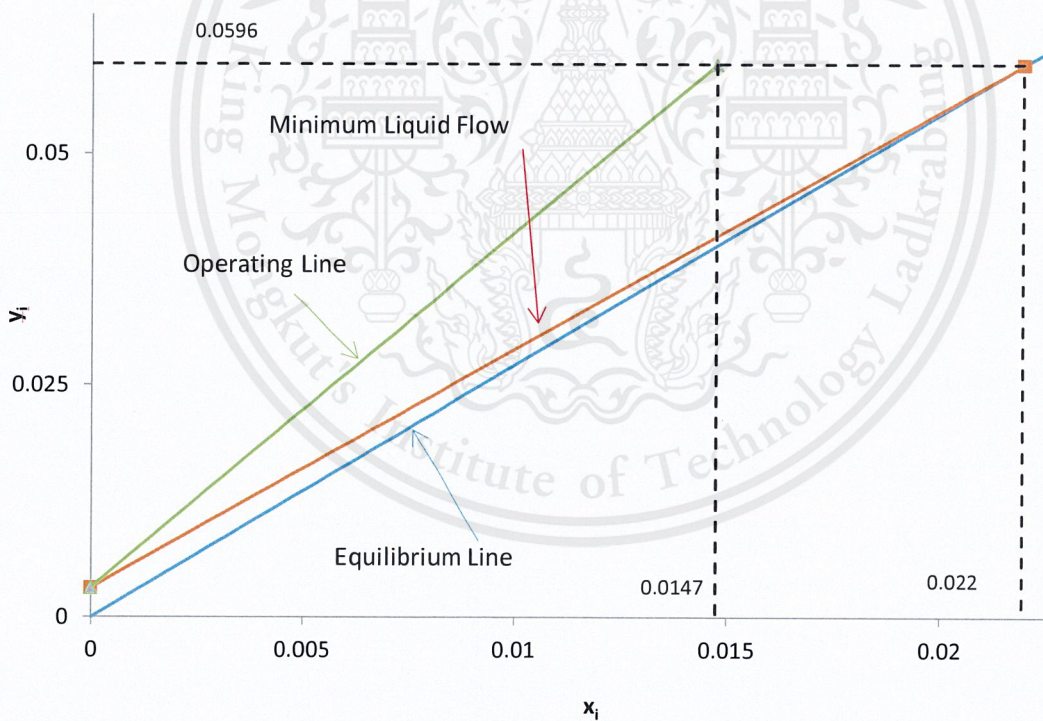


Figure E-1 Operating Line and Equilibrium Line

Mass Flux Calculation

Figure 3.4 is used to find flooding mass flux and operating mass flux. Abscissa is plotted in Figure 3.4 and read ordinate term that is used to calculate mass flux (See in Figure E-2). The ordinate term is 0.15 for flooding mass flux. Operating mass flux is 0.5 of flooding mass flux.

$$\text{Abscissa} = \left(\frac{L}{G}\right) \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \quad (3.22)$$

$$= \left(\frac{679\text{m}^3/\text{h} \times 1,005\text{kg}/\text{m}^3}{2.9 \times 10^5\text{m}^3/\text{h} \times 1.0\text{kg}/\text{m}^3}\right) \left(\frac{1.0\text{kg}/\text{m}^3}{1,005\text{kg}/\text{m}^3}\right)^{0.5}$$

$$= 0.0742$$

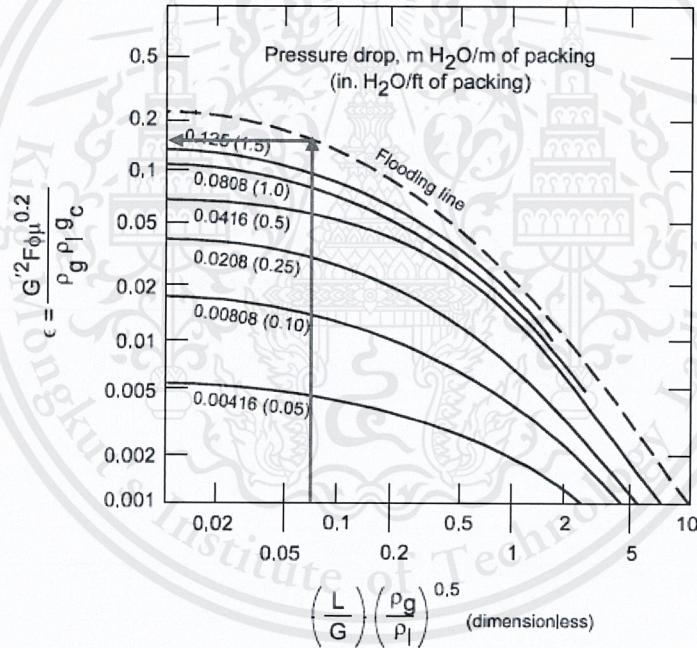


Figure E-2 Generalized Flooding and Pressure Drop Correlation at Flooding Condition

$$G' = \left[\frac{\epsilon \rho_g \rho_l g c}{F \phi \mu_l^{0.2}} \right]^{0.5} \quad (3.23)$$

$$= \left[\frac{0.15 \left(\frac{1.0\text{kg}}{\text{m}^3}\right) \left(\frac{1,005\text{kg}}{\text{m}^3}\right) (9.82\text{m}/\text{s}^2)}{131\text{m}^{-1} (1) (0.57\text{cP})^{0.2}} \right]^{0.5}$$

$$= 7.10 \text{ kg}/\text{m}^2\text{s}$$

$$G'_{\text{operating}} = 0.5 \times G' \quad (\text{E-5})$$

$$\begin{aligned}
 &= 0.5 \times 7.10 \text{ kg/m}^2\text{s} \\
 &= 3.55 \text{ kg/m}^2\text{s}
 \end{aligned}$$

The flooding mass flux is $7.10 \text{ kg/m}^2\text{s}$ and operating mass flux is $3.55 \text{ kg/m}^2\text{s}$.

Column Diameter and Packing Height Calculation

Column area is equal to air flow rate divided by mass flux. The area is 22.71 m^2 and diameter is 5.38 m .

$$\begin{aligned}
 A &= \frac{G}{G'_{\text{operating}}} & (3.24) \\
 &= \frac{2.9 \times 10^5 \text{ m}^3/\text{h} \times 1 \text{ kg/m}^3}{3.55 \text{ kg/m}^2\text{s}}
 \end{aligned}$$

$$= 22.71 \text{ m}^2$$

$$\begin{aligned}
 D &= \left(\frac{4A}{\pi} \right)^{0.5} & (3.25) \\
 &= \left(\frac{4(22.71 \text{ m}^2)}{\pi} \right)^{0.5} \\
 &= 5.38 \text{ m}
 \end{aligned}$$

Packed height uses number of transfer units and height of overall transfer units. The number of transfer units is 5.9 and height of overall transfer units is 0.57 . Total packing height is 3.39 m .

$$N_{OG} = \frac{\ln \left(\frac{y_1 - mx_1}{y_2 - mx_1} \right) \left(1 - \frac{mG_m}{L_m} \right) + \left(\frac{mG_m}{L_m} \right)}{1 - \frac{mG_m}{L_m}} \quad (3.26)$$

$$= \frac{\ln \left(\frac{0.0596 - 2.71(0.0147)}{0.0032 - 2.71(0.0147)} \right) \left(1 - \frac{2.71(9.42 \times 10^6 \text{ mol/h})}{2.53 \times 10^7 \text{ mole/h}} \right) + \left(\frac{2.71(9.42 \times 10^6 \text{ mol/h})}{2.53 \times 10^7 \text{ mole/h}} \right)}{1 - \frac{2.71(9.42 \times 10^6 \text{ mol/h})}{2.53 \times 10^7 \text{ mole/h}}}$$

$$= 5.9$$

$$H_{OG} = \frac{G'}{K_{OG}AP} \quad (3.27)$$

$$= \frac{3.55 \text{ kg/m}^2\text{s}}{\frac{2.6 \text{ mol}}{\text{h}} \text{ m}^3 \text{ Pa} (101.3 \text{ kPa}) 22.71 \text{ m}^2}$$

$$= 0.57$$

$$\begin{aligned}
 \text{Total Packing Height} &= N_{OG} \times H_{OG} \\
 &= 5.9 \times 0.57 \\
 &= 3.39 \text{ m}
 \end{aligned}$$

Pressure Drop Calculation

Pressure is found by Abscissa and ordinate term in Figure 3.4. The ordinate term is calculated at operating mass flux that is 0.0375. Pressure drop that is read from graph is 0.0312 m of H₂O/m of packing (See in Figure E-3). The total pressure drop of packing is 1.036 kPa.

$$\begin{aligned}
 \epsilon &= \frac{G'^2 F \phi \mu_l^{0.2}}{\rho_g \rho_l g_c} & (E-6) \\
 &= \frac{(3.55 \text{ kg/m}^2\text{s})^2 131 \text{ m}^{-1} (1)(0.57 \text{ cP})^{0.2}}{\left(\frac{1.0 \text{ kg}}{\text{m}^3}\right) \left(\frac{1.005 \text{ kg}}{\text{m}^3}\right) (9.82 \text{ m/s}^2)} \\
 &= 0.0375
 \end{aligned}$$

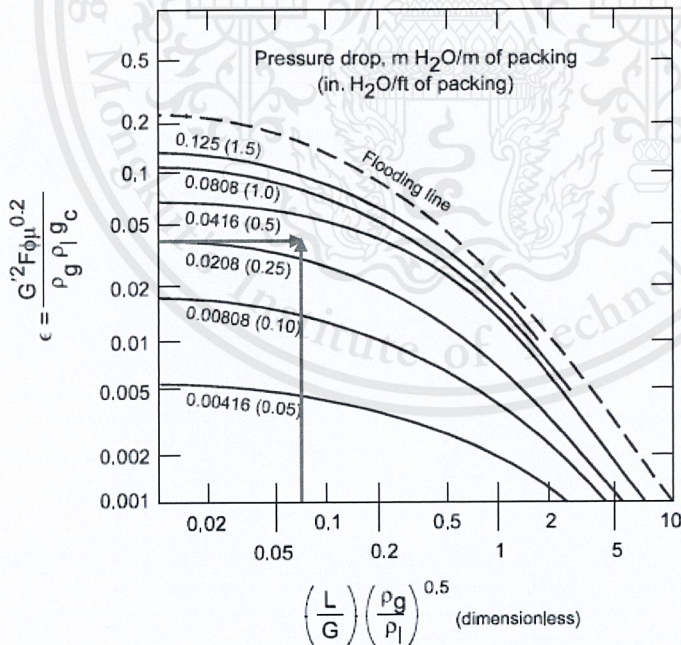


Figure E-3 Generalized Flooding and Pressure Drop Correlation at Operating Condition

$$\begin{aligned}
 \text{Total Pressure Drop} &= 0.0312 \times 3.39 \\
 &= 0.1056 \text{ m H}_2\text{O or } 1.0358 \text{ kPa}
 \end{aligned}$$

BIBLIOGRAHPY

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