Laboratory Scale Pressure Swing Adsorption Column

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Abstract

This study is aimed to design the process and select suitable equipment and instrument for further construction of adsorption unit. The adsorption process is designed according to pressure swing adsorption to separate CO_2 from the air. Process, equipment and instrument are designed for operate at pressure 10 bars and volumetric flow rate of mixed gas 1 to 10 L/min. The adsorption column is designed according to IS-2825 and IS-5522 standards. The 2.5 inches length 50 cm stainless steel pipe-type 304 sch 40 was selected as column. Head is design as ellipsoidal head with length 100 mm and crown radius 36.5 mm. The cylindrical part of head with 100 mm length is added to allow fluid fully developed before contact with the adsorbent. There are three control system in the process including flow control loop, automatic inlet switching and pressure control loop. The flow control loop is using to control volumetric flow rate of inlet gas. The automatic inlet switching is using to switch inlet between columns. In the adsorption column, pressure is controlled by a pressure control loop. Main instrument of the control loop is including pressure controller, pressure transmitter, actuator and control valve. Pressure controller is assembled based on Arduino. Result of the pressure controller from Arduino, is capable to control pressure in the range of 0 to 16 barg. All instruments are selected by suitable operating condition and appropriate expenditure.

Keywords: Pressure wing adsorption, CO_2 adsorption, Arduino, Pressure control

เรื่อง หอดูดซับแบบสลับความดัน
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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อออกแบบระบบ และเลือกอุปกรณ์ที่เหมาะสมสำหรับสร้างหน่วยดูดซับในอนาคต กระบวนการการดูดซับได้ออกแบบตามกระบวนการการดูดซับแบบสลับความดันเพื่อแยกก๊าซคาร์บอนไดออกไซด์ออกจากอากาศ กระบวนการและ อุปกรณ์ต่าง ๆ ถูกออกแบบให้สามารถดำเนินการได้ที่ความดัน 10 บาร์ และอัตราการไหลเชิงปริมาตรของก๊าซขาเข้าที่ 1 ถึง 10 ลิตรต่อนาที การออกแบบหอดูดซับแบบความดันสูงสอดคล้องกับมาตรฐาน IS2825 และ IS5522 ท่อแสตนเลส 304 sch 40 ขนาด 2.5 นิ้ว ยาว 50 เซนติเมตรถูกใช้เป็นหอดูดซับ ส่วนหัว (Head) ของหอดูดซับเลือกใช้ ellipsoidal ที่มีความยาว 100 มิลลิเมตรและ มีรัศมีส่วนโค้ง (crown radius) 36.5 เซนติเมตร ซึ่งส่วนหัวที่เป็นทรงกระบอกขนาด 100 มิลลิเมตรถูกใส่เข้ามาเพื่อให้ของไหลเข้าสู่ช่วง fully developed ภายในกระบวนการมีระบบควบคุมสามระบบได้แก่ ระบบความคุมการไหล ระบบเปลี่ยนทิศการไหลของแก๊สขาเข้า และระบบควบคุมความดัน ระบบควบคุมการไหลใช้เพื่อควบคุมอัตราการไหลเชิงปริมาตรของก๊าซขาเข้า ระบบเปลี่ยนทิศการไหลของแก๊สขาเข้าถูกใช้เพื่อสลับก๊าซขาเข้าระหว่างหอดูดซับ ความดันภายในหอดูดซับจะถูกควบคุมด้วยระบบควบคุมความดัน อุปกรณ์หลักของระบบควบคุมความดันประกอบด้วยเครื่องส่งสัญญาณความดัน อุปกรณ์ควบคุมความดัน actuator และวาล์วควบคุม อุปกรณ์ควบคุมความดันที่ใช้ในงานนี้ประกอบขึ้นจาก Arduino ผลของอุปกรณ์ควบคุมความดันนั้นสามารถควบคุมความดันได้ในช่วง 0 ถึง 16 บาร์ ซึ่งอุปกรณ์ทั้งหมดนั้นถูกเลือกให้เหมาะสมกับสภาวะการใช้งาน และภายใต้งบประมาณที่จำกัด

คำสำคัญ: การดูดซับแบบสลับความดัน, การดูดซับก๊าซคาร์บอนไดออกไซด์, Arduino, อุปกรณ์ควบคุมความดัน

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NOMENCLATURE

AR	Aspect ratio
f_p	Circumferential stress
CV	Control valve
D_i	Inside diameter
p	Internal pressure
J	Joint efficiency
L_{bed}	Length of bed
f_a	Longitudinal stress
D	Mean diameter of shell or bed
M	Motor actuator
D_o	Outside diameter
PIC	Pressure controller
$\Delta P/_{z}$	Pressure drop per unit length
PSA	Pressure swing adsorption
PT	Pressure transmitter
V	Stress intensification factor
TSA	Thermal swing adsorption
ΔP_{tot}	Total pressure drop
VOC	Volatile organic compound

CHAPTER I
INTRODUCTION

1.1 Background

The adsorption unit is an essential unit in chemical industries. It was used for separation and purification. Hence, the knowledge of adsorption unit is required for chemical engineering student. The application of adsorption unit are air pollution reduction, removal moisture and humidity, removal sulfur from natural gas, removal CO_2 from biogas, and etc[1]. The reduction CO_2 emission from fossil fuel burning in industrial and human activity is important to mitigate global warming crisis[2]. Carbon capture technologies are important to reduce CO_2 emission. There are several processes to capture CO_2 such as absorption, adsorption, chemical looping, membrane gas separation[3]. From those process, the adsorption and absorption are popular processes for capture CO_2. Both of process have advantages and disadvantages. The advantages of absorption are simple operation and easy to maintenance, but the disadvantage are large construction and large volume of water usage. The advantage of adsorption is low energy requirement. However, when adsorbent is saturated, it is required to stop a process to desorp[4]. Indeed, single adsorption unit has low efficiency. Therefore, pressure swing adsorption is invented to increase efficiency and capable for continuous operation. Currently, the adsorption unit for unit operation laboratory is in run-down condition. For this reason, this project is aimed to design equipment and instrument for a pressure swing adsorption column for using in a laboratory.

1.2 Objectives

1) To design process for pressure swing adsorption.
2) To design appropriate equipment and instrument for pressure swing adsorption.

1.3 Scopes of Work

1) Design of pressure swing column according to IS-2825, IS 5522 standards.
2) Design and selected instrument for the pressure swing adsorption that capable to operate at gas flow rate 1 to 10 L/m and pressure in column 1 to 10 bar.

1.4 Expected Outputs

1) Pressure column for pressure swing adsorption process.
2) Instruments for pressure swing adsorption and automatic system.

CHAPTER II
LITERATURE REVIEW

This chapter discussed about the theoretical of adsorption, mechanism of gas adsorption, classification of adsorbent, adsorption systems and related literature to cultivate the information to design and construct laboratory scale pressure swing adsorption.

2.1 Adsorption

Adsorption is accumulation processing occur at interphase between two phases of fluid and solid when concentration of solute in fluid is higher than solid particle and diffuse to surface of solid. Similarly, reverse operation, desorption will bring solutes from solid particle out. The molecule of substance which is adsorbed called "Adsorbate" and solid particles called "Adsorbent". The adsorption process is possible to occur "Physisorption" or "Chemisorption" which depend on adsorption force[5].

2.1.1 Adsorption forces

Adsorption forces are divided into two type including physical adsorption or physisorption and chemical adsorption or chemisorption.

1) Physisorption

Physisorption is causing by Vander Waals forces which attract atoms and molecules together, there are two unique properties. Firstly, all atoms and molecules attach another with mechanism such as cohesion of inert gases in the solid and liquid phase, physical adsorption of adsorbate on adsorbent. Secondly, it still significant even the molecules far apart which consist Vander Waals forces consist of London dispersion force and Electrostatic force[4 6].

The London dispersion force is weakest force of intermolecular force. The London dispersion force is occurred when electron form temporary dipoles with another electron. An atoms or molecules capable to temporary dipole when unsymmetric distribution of electrons occurred, which shown in Figure 2.1.

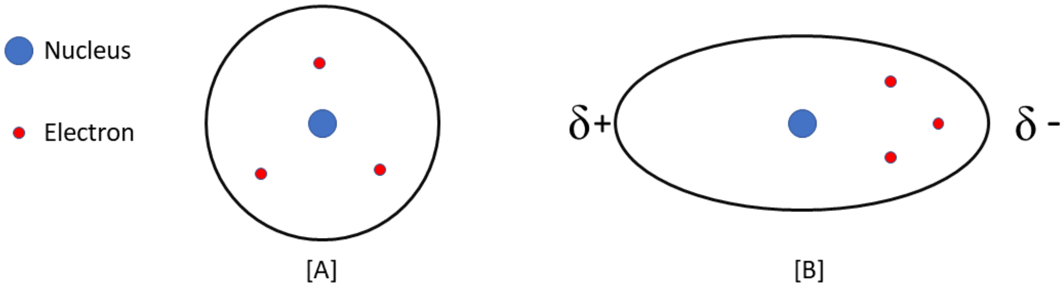

Figure 2.1: Show symmetric distribution [A] and unsymmetric distribution [B] of electrons [7].

The first of dipole atoms or molecules can be induce another atoms or molecules to be dipole and it is motived of "Electrostatic force" between two of atoms or molecules, which shown in Figure2.2 [7].

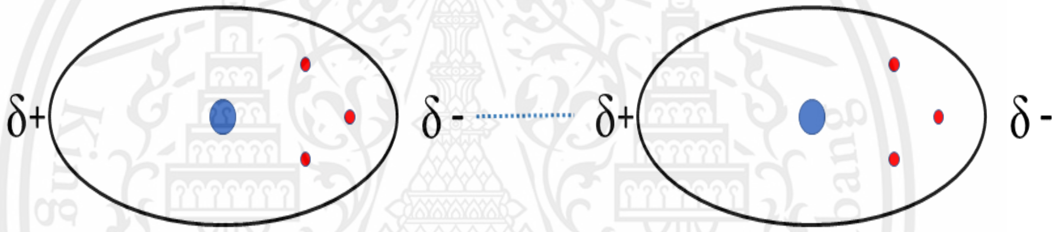

Figure 2.2: Electrostatic force between two atoms[7].

The heat of adsorption is released approximately 25 to 40 kJ/mole when physisorption occur which is very small amount of energy requirement[8]. Therefore, the regeneration process of physisorption is required low energy[9].

2) Chemisorption

Chemisorption or chemical adsorption is occurred when electrons of atoms or molecules are sharing between adsorbate and adsorbent to create ionic or covalent bond. Hence, chemisorption not capable to fully reversible, and the regeneration process required high energy (200 to 400 kJ/mole). Chemisorption, gas molecules are adsorbed on the surface of adsorbent with valence bonds and monolayer form are observe[9].

Chemisorption is capable to occur only monolayer adsorption. In other hand, physisorption is capable to occurred both mono and multilayer adsorption, which show in Figure 2.3.

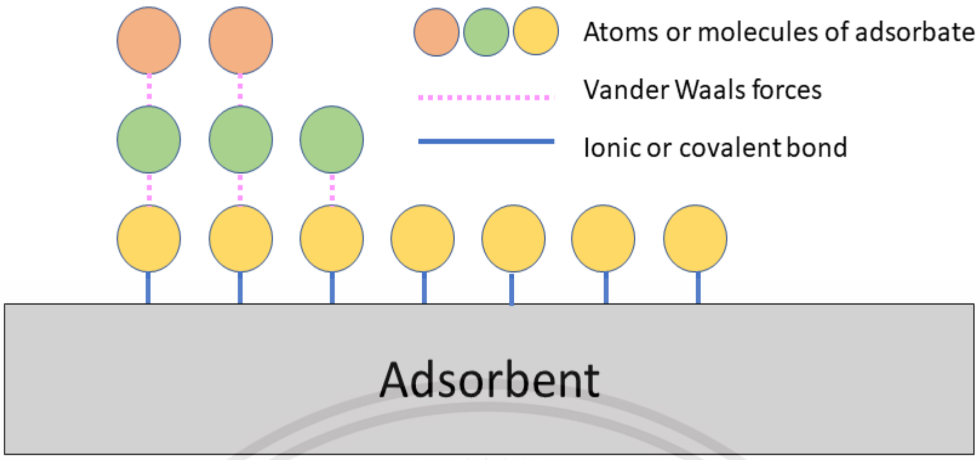

Figure 2.3: Monolayer and multilayer adsorption[10].

2.1.2 Mechanism of gas adsorption

Adsorption which occurred between two phases are solid and gas, the gas will adsorb on surface of porous surface, there are three steps.

First step: the solute in gas diffuse from bulk fluid through boundary layer to adsorbent surface, the amount of solute which adsorbed depend on mass transfer coefficient and driving force. The gas diffuses to surface of adsorbent shown in Figure 2.4.

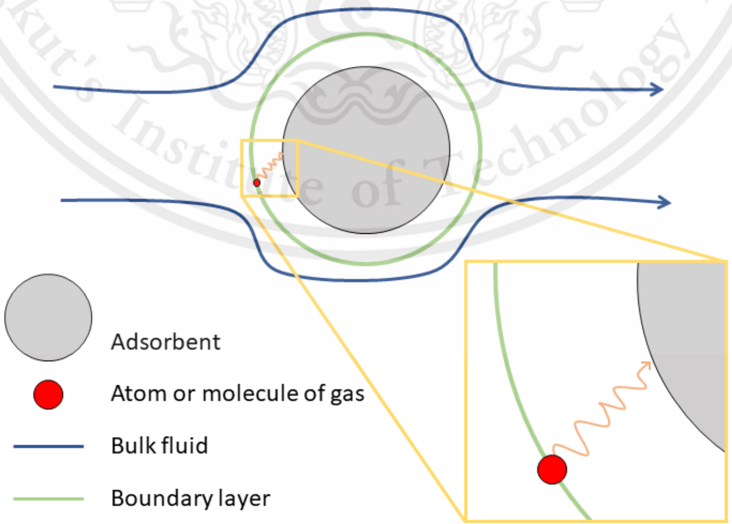

Figure 2.4: The gas atom diffuses through boundary layer to surface of adsorbent [11].

Second step: the molecules of adsorbate diffuse from pore mouth through pores of adsorbent called "Internal diffusion" which involves with size of molecules adsorbate and pores size. The internal diffusion of adsorbate molecules shown in Figure 2.5.

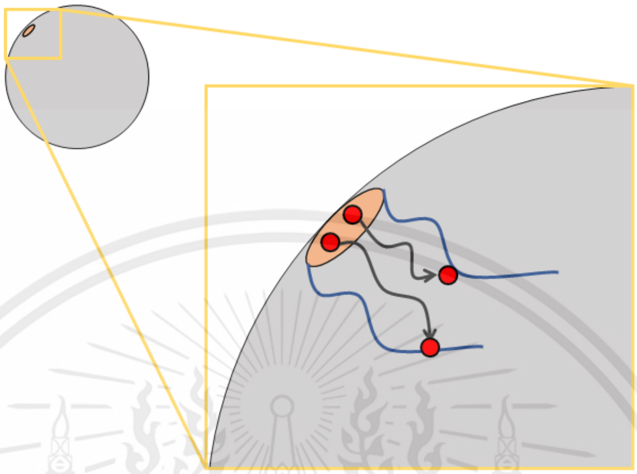

Figure 2.5: The internal diffusion of adsorbate molecules [11].

Third step: the molecules of adsorbate are adsorbed by monolayer or multilayer buildup on pore surface. The internal diffusion is increasing with large pore size while the small pore size, the molecules of gas are colliding with pore wall and move through the adsorption site.

2.1.3 Adsorbent

Most of solid are capable to adsorb solute from fluid. However, only some solid have enough selectivity and capacity for commercial adsorbent. Especially, the specific surface area, which depend on manufacturing technique. Adsorbent usually are use in from of pellets, spherical, or rod. The properties of adsorbent in commercial application should be have (1) high selectivity, (2) high capacity to minimize volume of column and amount of sorbent, (3) suitable for rapid sorption, (4) appropriate thermal and chemical stability, (5) suitable mechanical strength, (6) a free-flowing tendency to facilitate vessels, (7) long time usage with low fouling, (8) no tendency to produce undesired substance or reaction, (9) capable to regenerate or desorb high molecular weight substance, and (10) not expensive[12].

1) Classification and characterization of adsorbent

Adsorbents are classified into three classes, which represent in Table 2.1.

Table 2.1: Classification of adsorbent[13]

Class	Adsorbent	Surface
Class I	Graphitized carbon black	Graphitic carbon
Class II	Activated silica gel	Oxide of silica gel
Class III	Activated charcoal	Oxide of amorphous carbon
	Carbon molecular sieves	Amorphous carbon
	Porous polymer	Organic "plastics"

Class I adsorbent is interacted with non-specific type of adsorbate. Graphitized carbon black (GCB) is homogeneous surface material without micro pores. GCB adsorbs substance only on external surfaces based on shape and molecular size of adsorbate. GCBs prepared by heating conventional carbon blacks to 3000°C on atmospheric pressure with inert gas. The elimination of volatile, tar and the crystallization of graphite to arrange in form of polyhedrons. The functional groups on the carbon black surface are destroyed and there are almost free of unsaturated bonds, free radical, and ions.

The adsorbates are adsorbed on the GCB with availability of two types of adsorption sites. The major of adsorption sites are non-polar, and carbon arrange corresponding to graphite. These sites represent no tendency to interact with functional groups and dispersive interactions dominate the retention behavior. The minor adsorption site is polar adsorption site, which is robust interaction with polar compounds.

Class II and III adsorbent are interacted with both of non-specific and specific type of adsorbates[13]. Silica gel is an amorphous silicon dioxide, which chemically inert and non-toxic material. It has micropores with high surface area, which physical and chemical structure not capable to transform[14]. Silica gels are able to classify into three type, regular, intermediate, and low density. Regular density silica gel is having surface area around 750 square meter per gram. Intermediate and low density silica gel are have surface area approximately 350 and 150 square meter per gram respectively[15]. The limitation of silica gel has high selectivity with water.

Class III adsorbent consist of activated carbon, carbon molecular sieves, and porous polymers. Activated carbon is an amorphous carbon, which been used for medical purposes since the time of ancient Egyptians. The source of commercial activated carbons are produced from biomass, wood, coal, coconut shell, and petroleum acid sludge. Typically activated carbons are produced two-step process of carbonization and activation. Carbonization is a process, which produce charcoal by pyrolysis substance at 400 to 900°C to fully remove volatile compounds with high percentage of fixed carbon remain[16]. Then activation with oxidizing gases such as CO_2, CO_2 mixed with N2 or air at atmospheric and increase temperature to 800 to 1100°C. This method is able to produce activated carbon with large surface area and good physical properties, which is an inexpensive process. However, this process are required high energy and longtime of activation process[17].

Carbon molecular sieves are produced from pyrolysis of polymeric material or petroleum pitch at temperature above 400°C, which produce high porous structure with almost fully uniform structure, there are small amount of crosslink to disordered pore structure. Carbon molecular sieves are having high surface are and micropores structure with organic compound, but it can be easily to contaminated by impurities from air. The particle size and distribution of pores and size are depended on starting material and carbonization process. The homogenous of pores structure is decreasing by impurity of polymeric substance[13].

Several properties of adsorbent should be considered, to select suitable adsorbent for each process. The properties which consider are pore diameter, particle porosity, density, surface area, and capacity for H_2O vapor are shown in Table 2.2.

Table 2.2: Properties of commercial adsorbent[12].

Adsorbent	Pore diameter (Å)	Particle porosity	Particle density (g/cm3)	Surface area (m2/g)	Capacity for H2O vapor (wt%)
Silica gel:					
Small pore	22.26	0.47	1.09	750-850	11
Large pore	100-150	0.71	0.62	300-350	-

Table 2.2: Properties of commercial adsorbent (Continue).

Adsorbent	Pore diameter (Å)	Particle porosity	Particle density (g/cm3)	Surface area (m2/g)	Capacity for H2O vapor (wt%)
Activated carbon:					
Small pore	10-25	0.4-0.6	0.5-0.9	400-1200	1
Large pore	>30		0.6-0.8	200-600	-
Molecular-sieve carbon	2.10	-	0.98	400	-

2.1.4 Adsorption system

Many types of equipment configuration and operating procedures are using for commercial adsorption separation processes. the most used equipment configurations and operating procedures are in the Table 2.3.

Table 2.3: Common commercial method for adsorption and regeneration[12].

Feed phase	Contacting equipment	Adsorbent regeneration method	Main application
Liquid	Agitator vessel	Adsorbent discarded	Purification
Liquid	Fixed bed	Thermal reactivation	Purification
Gas	Fixed bed	Thermal swing (TSA)	Purification
Gas	Fixed bed	Inert-purge swing	Purification
Gas	Fixed bed	Pressure swing (PSA)	Bulk separation

Adsorption processes are able to classify into three method, show in Figure 2.6. The agitator vessel is used with liquid batch, which added small particle of adsorbent to form slurry. The external resistance and internal resistance of mass transfer is small, because of small particle of adsorbent and with good agitation. The residence time is depended on how fast equilibrium is occurred. The application of this process is to remove small amount of solute and large molecules, such as color agent, from water. The filtration and sedimentation are required to remove adsorbent from slurry, which capable to continuous operate also called “contact filtration”.

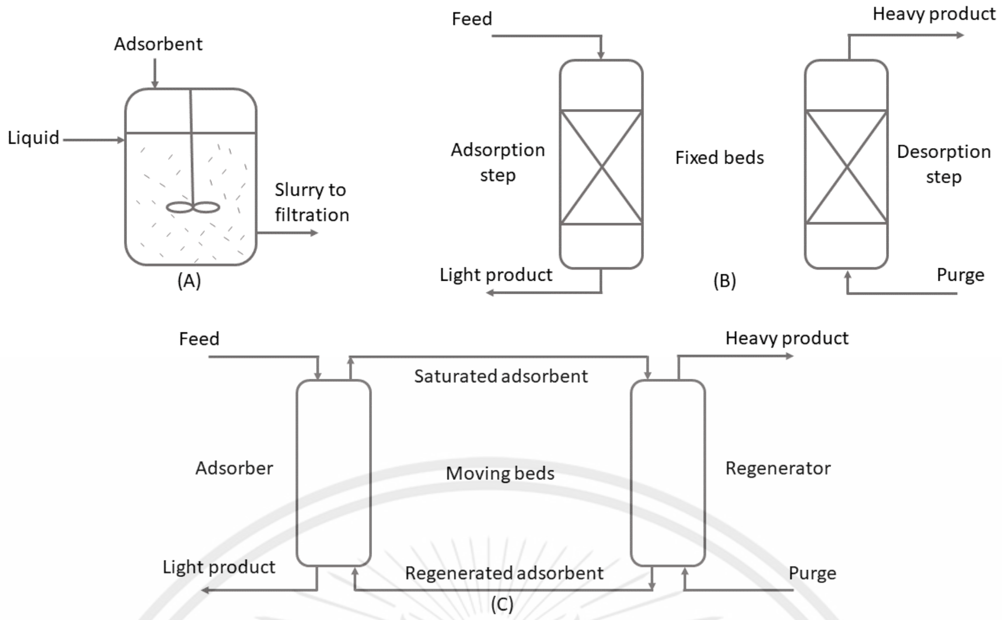

Figure 2.6: Modes of adsorption. Stirred-tank slurry, operation (A). Cyclic fixed-bed, batch operation (B). continuous countercurrent operation (C)[12].

Cyclic-fixed bed mode is using for both liquid and gas phase feed. Particle size of adsorbent is affected to pressure drop in column and transfer rate of solute. Hence, both of them are mainly factors to select particle size of adsorbent. To avoid fluidizing of bed during adsorption, feed should flow in the top of column. Occasionally, the spent adsorbent is brought out from vessel to reactivated at high temperature. Adsorbents of fixed bed are always regenerated by method in Table 2.3.

2.1.5 Pressure swing adsorption

Pressure swing adsorption (PSA) cycle, adsorption process is occurred when increasing of pressure, where desorption occurred at nearly atmospheric. PSA is use for separations because depressurized and repressurize capable to rapidly process, which possible to operated small time of cycle. If adsorption has arisen at near atmospheric pressure and desorption under vacuum, it called "vacuum swing adsorption" . PSA is widely use to separation of air. If a carbon molecular sieve adsorbent is used, oxygen diffusivity is observed more than nitrogen about 25 times. The resulting high-pressure gas is almost pure nitrogen, represent in Figure 2.7. In the large plant, VSA is using because it require low energy[12]. PSA is used for volatile organic compounds (VOCs) removal and recycle. For VOCs removal and recycle, commercial activated carbon adsorbent is selected. The industrial parameters are consisting of none-equilibrium time, effective length and enrichment ratio[18].

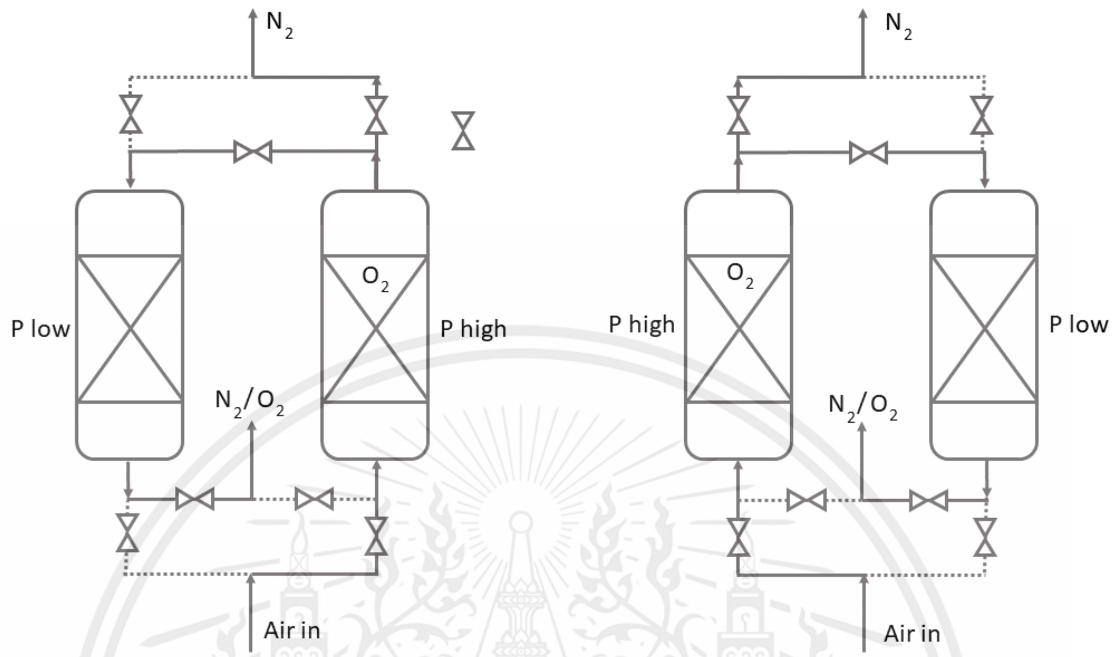

Figure 2.7: Illustrate of pressure swing adsorption[19].

To recovery CO_2 from flue gases from industries, which have carbon dioxide around 15 to 35% of concentration. Many adsorbents are capable to strongly adsorb CO_2 such as zeolites and carbon molecular sieves on vacuum swing adsorption. Resulting 99% purity and 80% recovery of CO_2 product. To recovery methane from biogas, which contain 50 to 65% of methane, 35 to 50% of CO_2 and small amount of nitrogen, hydrocarbon, and sulfur. Recovery process using two-stage process, first stage is using activated carbon to removed hydrogen sulfide. Second stage is removal of heavier hydrocarbons by activated carbon adsorbent. The final stage, VSA and carbon molecular sieves are used to adsorb CO_2, N_2 and O_2 with 87 to 89% result methane gas[19].

2.2 Equipment design

This part will be discussed about column design, which including operating condition, selection of material, design stress, shell design, head cover, flange joint, and standard usage. Column of pressure swing adsorption is classified as pressure vessels.

2.2.1 Operating conditions

Most of pressure vessels are spherical or cylindrical with domed head. Normal condition of pressure vessel, which should be consider are including

1) Operating pressure.
2) Operating temperature: minimum, maximum temperature and fluid temperature.
3) Influent of environment such as chemical corrosion and erosion.
4) External loading by wind, snow, and piping system.

2.2.2 Selection of material

Material of pressure vessel is selected by operating conditions, mechanical properties, corrosion resistance, fabrication problems, commercially available material and costing. Metallic materials are capable to classify into three groups.

1) Low-cost material including cast iron and low steel alloy.

2) Medium-cost material including high alloy steel , aluminum, copper, nickel, and lead.

3) High-cost material including platinum, silver, titanium, and zirconium. Large scale industries are mainly used first group, which used second and third groups as bonding or cladding.

1) Steel

Steel is most multipurpose and widely used material for pressure vessel. Usually, steel for pressure vessel contain limited 0.3% carbon. Low alloy steels which used for high temperature contained of 0.15% carbon, manganese, chromium and molybdenum. Low alloy steels are developed for high temperature with lower elongation to rupture than conventional mild steels. High alloy steels are used for avoiding high corrosion from contaminated fluid and severe duty[20].

2) Aluminium and aluminium alloy

Aluminium alloys are developed for high mechanical properties. It is simple to fabricate and capable to save ductility at low temperature. Aluminium alloys are most used for organic solvent, nitric acid, sea water and inorganic salt. The main disadvantage of aluminium alloys is low melting point[20].

3) Nickel and nickel alloys

Nickel alloys are used for handling corrosive fluid at low and high temperature, which is important to prevent contamination of fluid. Aluminium alloys are very expensive material. The mainly application is cladding[20].

4) Copper and copper alloys

Copper alloys are used in food manufacturing, recovery of organic solvent and mainly used in heat exchangers and evaporator for general purpose[20].

2.2.3 Design condition and stresses

Pressure and temperature are primary specification for pressure vessel. The pressure vessel must be protected by safety devices such as relief valves or bursting discs. Safety devices are design at maximum pressure or temperature plus 10%[20].

1) Design condition

Major parameters, which should be consider for gas adsorption are including

1) Gas flow rate.
2) Concentration of contaminants.
3) Temperature of gas stream.
4) Relative humidity of gas stream.
5) Allowable pressure drop

Pressure drop in the column is depending on adsorbent particle size, contact time and surface loading rate. Surface loading rate is expressed as volume of vapor per cross-sectional area of bed (m^3/m^2)[21].

2) Design stress (allowable stress)

From each standard the allowable stress is based on ultimate tensile stress, yield stress or 0.2% proof stress or properties of creep. The design stress is achieved by using a safety factor from reference standard, which shown in Table 2.4.

Table 2.4: Example of safety factors by different standard code[20].

Standard code	a (U.T.S)	b (Y.S)	c (S_R)	d (S_C)
ASME VIII Div. 1-‘68	3.0	1.5	-	1.0
BS-5500-‘76	2.35	1.5	1.3	1.0
IS-2825-‘69	3.0	1.5	1.5	1.0
RAP de Gaz	3.0	-	-	-
ANCC code	-	1.5	1.5	-
ISO-TC-11	2.4	1.5	1.6	1.0

a is safety factor on ultimate tensile stress.

b is safety factor on yield stress.

c is safety factor on S_R.

d is safety factor on S_C.

S_R is average stress of rupture after 100,000 hours at operating temperature (kg/cm^3)

S_C is average stress for 1% creep in 100,000 hours at operating temperature (kg/cm^3)

The allowable stress is depended on material and temperature. Pressure vessels are design under the assumption of steady pressure. The external loading are significant essential when design of large vessels. Some of standard codes suggest low design stress to cover effect of external loading[20].

2.2.4 Design of column and components

The pressure vessels are simplest of design and fabrication. The pressure vessel components are capable to divided by following:

1) Shell
2) Head or cover
3) Nozzle
4) Flanged joint
5) Support

Most of them are construct from metal sheets, plates and joint by welded or flange. If joint by welding, joint efficiency must be considered. The joint efficiency is depended on types of weld and inspection, which show in Table 2.5.

Table 2.5: Show the joint efficiency[22].

Types of weld		Joint efficiency, J		
		Fully inspection	Spot inspection	Not inspection
	Butt joint by double-welding	1.0	0.85	0.7
	Single weld butt joint with back strip	0.90	0.80	0.65
	Double full fillet lap joint	-	-	0.60
	Single full fillet lap joint without plug welds	-	-	0.45
	Single full fillet lap joint with plug welds	-	-	0.50

1) Shell or column design

For cylindrical shell, pressure in the column is risen stress of shell wall, which including circumferential and longitudinal stress following equation 2.1 and 2.2, respectively.

$$f_p = \frac{pD}{2t} \qquad 2.1$$

$$f_a = \frac{pD}{4t} \qquad 2.2$$

f_p is circumferential stress

f_a is longitudinal stress

p is internal pressure

D is mean diameter of shell

Both of them are tensile stress. Generally, circumferential stress is used as design stress because it greater than longitudinal stress. The thickness of shell is giving by standard code IS2825 following equation 2.3 to 2.5.

$$t = \frac{pD}{2fJ} \quad 2.3$$

$$t = \frac{pD_i}{2fJ\text{-}p} \quad 2.4$$

$$t = \frac{pD_o}{2fJ + p} \quad 2.5$$

f is allowable stress

J is joint efficiency

D_o is outside diameter

D_i is inside diameter

D is mean diameter ($D_o \approx D_i$)

p is design pressure

The allowable stress (A.S), ultimate tensile stress (U.T.S) and yield stress (Y.S) of each material and standard code are show in Table 2.6.

Table 2.6: Minimum tensile stress, yield stress, and allowable stress of each standard at ambient temperature[20].

Material	**U.T.S (N/mm^2)**	**Y.S. (N/mm^2)**	**A.S (N/mm^2)**		
			ASME-VIII, DIV.I	IS-2825	BS-5500
Carbon steel	420.0	210.0	104.8	140.6	140.6
At 515 Gr 70	492.2	267.2	137.9	163.8	178.6
At 515 Gr 70 at 400 °C	413.4	186.3	111.0	124.4	124.4
Stainless steel A240 type 304	527.3	210.9	137.9	140.6	140.6

The adsorption column is sizing based on GPSA Databook and exploding the limits of adsorption-based CO_2 capture design to process economics.

Firstly, to calculate gas velocity at design pressure drop per unit length of bed ($\frac{\Delta P}{z}$). The recommendation of maximum pressure drop per unit length is 0.33 psi/ft. For modified Ergun equation parameters given x1 and x2 equal to 0.238 and 0.00021 respectively, which replace in equation 2.6[23].

$$x_2\, \rho_{T,P}^{gas} V_{gs}^2 + x_1 \mu V_{gs}^2 = \frac{\Delta P}{z} \qquad 2.6$$

ρ is gas density at operating pressure and temperature (lb/ft^3)

μ is gas viscosity (cP)

V_{gs} is superficial gas velocity through the bed (ft/min)

The length of bed is calculated from total pressure drop (ΔP_{tot}) and pressure drop per unit length, which total pressure drop is recommended between 4 to 8 psi.

$$L_{bed} = \frac{\Delta P_{tot}}{\Delta P/_{z}} \qquad 2.7$$

The dimeter of bed is calculated from aspect ratio. The aspect ratio (AR) is common range of 2 to 5[24].

$$D = \frac{L_{bed}}{AR} \qquad 2.8$$

2) Head or cover design

To close the shell a cover is importance, which capable to attach with shell by weld or flange joint. There are many types of covers, which selected by different operating pressure. Formed heads are most simple, which used at atmospheric pressure. Torispherical heads are used for low pressure at range 1 to 15 bar. Ellipsoidal heads are suitable for pressure higher than 15 bar. Hemispherical heads are most strong and expensive. There are shown in Figure 2.8.

Figure 2.8: Types of cover and heads. Form head [A], torispherical head [B], ellipsoidal head [C] and hemispherical head[D][20].

The ellipsoidal and hemispherical head are widely used with cylindrical shell. The thickness of head covers are calculated based on circumferential stress, which due to internal pressure. The thickness of elliptical head and hemisphere head are calculated from equation 2.9 and 2.10, respectively.

$$t_h = \frac{pDV}{2fJ} \qquad 2.9$$

p is internal pressure

D is major axis of ellipse

V is stress intensification factor = $\frac{1}{6}(2 + k^2)$

$$k = \frac{\text{major axis}}{\text{minor axis}}$$

k is commonly as 2 making V=1.0

$$t_h = \frac{pD_o}{4fJ + p} = \frac{pD_i}{4fJ\text{-}p} \qquad 2.10$$

CHAPTER III
RESEARCH METHODOLOGY

This chapter is described about how the process of pressure swing adsorption design, equipment design and instrumentation.

3.1 Process design

Adsorption process is design as pressure swing adsorption to study how to separate CO_2 from air. Block flow diagram of pressure swing adsorption is shown in Figure 3.1. CO_2 from tank is mixed with compressed air at three-way fitting, then mixed gas flowน to the one of adsorption column. The first column are fully adsorbed, automatic system would switch mixed gas to another column. The outlet gas second column is used to desorb adsorbent of the first column.

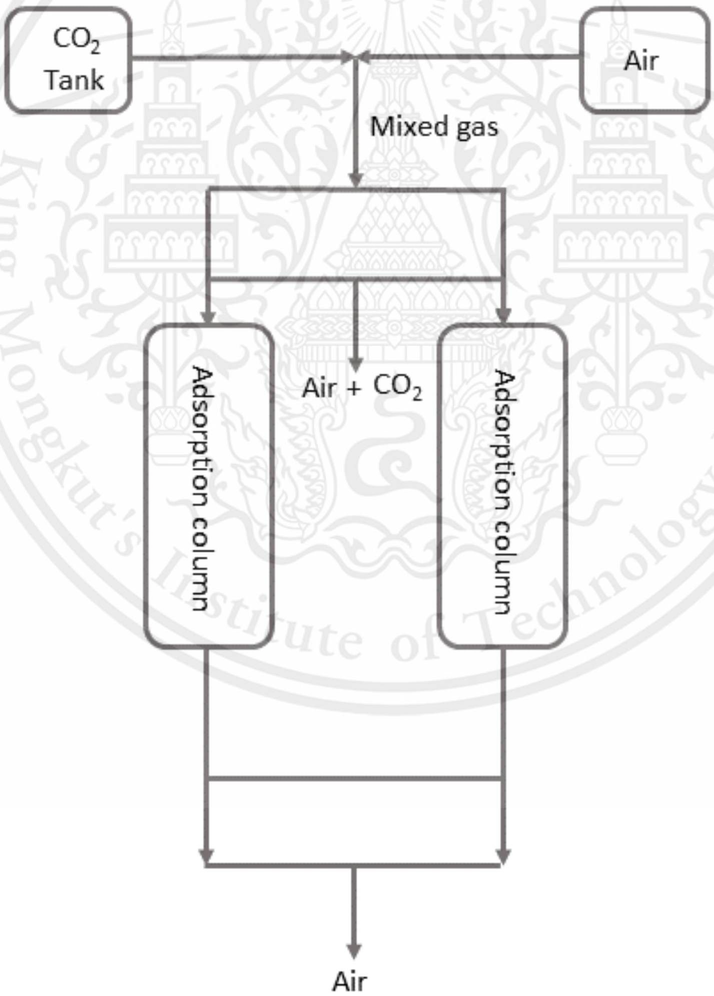

Figure 3.1: Block flow diagram of pressure swing adsorption.

3.2 Equipment design

To design equipment and selected instrument for the pressure swing adsorption that capable to operate at gas flow rate 1 to 10 L/m and pressure in column 1 to 10 bar.

3.2.1 Column body design

Steps of column design are shown below,

1) Selected material of column.

2) Design approximately diameter and thickness of column, which is appropriated with operating condition such as pressure, gas flow rate and etc.

3) Selected the pipe which is close to size column from 2), then calculated the allowable stress by equation 2.1

$$f_p = \frac{pD}{2t} \qquad 2.1$$

Calculation example

Stress of column at outside diameter (D) = 73 mm

operating pressure (p) =10 bar

wall thickness (t) = 5.16 mm

$$f_p = \frac{pD}{2t}$$

$$f_p = \frac{(10bar)(73mm)(0.1N/mm^2)}{2(5.16mm)(1bar)}$$

$$f_p = 7.073\,\frac{N}{mm^2}$$

4) Multiplied the calculated design stress by safety factor from Table 2.4 which is depended on standard used. The calculation are shown in appendix A.

5) Compared the design stress from 4) to allowable stress in Table 2.6.

6) Calculated the length of columns based on design volume of bed.

3.2.2 Heads or cover design

Steps of head design are shown below,

1) Selected type of head cover, which suitable to design pressure.

2) Calculated the thickness of head cover or used thickness equal to column, which depend on type of heads.

3) Simulation of fluid flow to find suitable length. Compared flow simulation of fluid in head with distributor and without distributor to find more suitable length.

3.2.3 Fabrication

Steps of fabrication are shown below,

1) Create a detailed mechanical design of pressure column and accessory.

2) Place a manufacturing order of pressure column.

3.3 Instrumentation

1) Select instrument which related and suitable with operating condition including pressure transmitter, pressure controller, motor actuator, solenoid valve, control valve and composition of pressure controller.

2) Install composition of pressure controller on Arduino board.

3) Coding both of pressure controller and automatic switching inlet of fluid. The codes are shown in appendix C.

4) Assembly pressure transmitter to pressure controller. Calibrating pressure controller and pressure transmitter by connected pressure transmitter to column then increase pressure and measure output signal by multimeter.

5) Connect the solenoid valves and its component to Arduino board to test automatic switching of solenoid valves.

CHAPTER IV
RESULTS AND DISCUSSION

This chapter is discussed about the detailed-on column design, control loop and instrumentation of pressure swing adsorption system.

4.1 Pressure column design

Pressure columns consist of column body and head.

4.1.1 Column body design

The 2.5 inches stainless steel pipe-type 304 sch 40s was selected as material for column body. The design pressure of column is 10 bars provided stress 21.2 which is not over the allowable stress in IS-2825 standard. The column length is 50 cm and yield internal volume are 2.0 liters. At the top and bottom of column, there are flange connector. The dimension of pressure column is show in Figure 4.1.

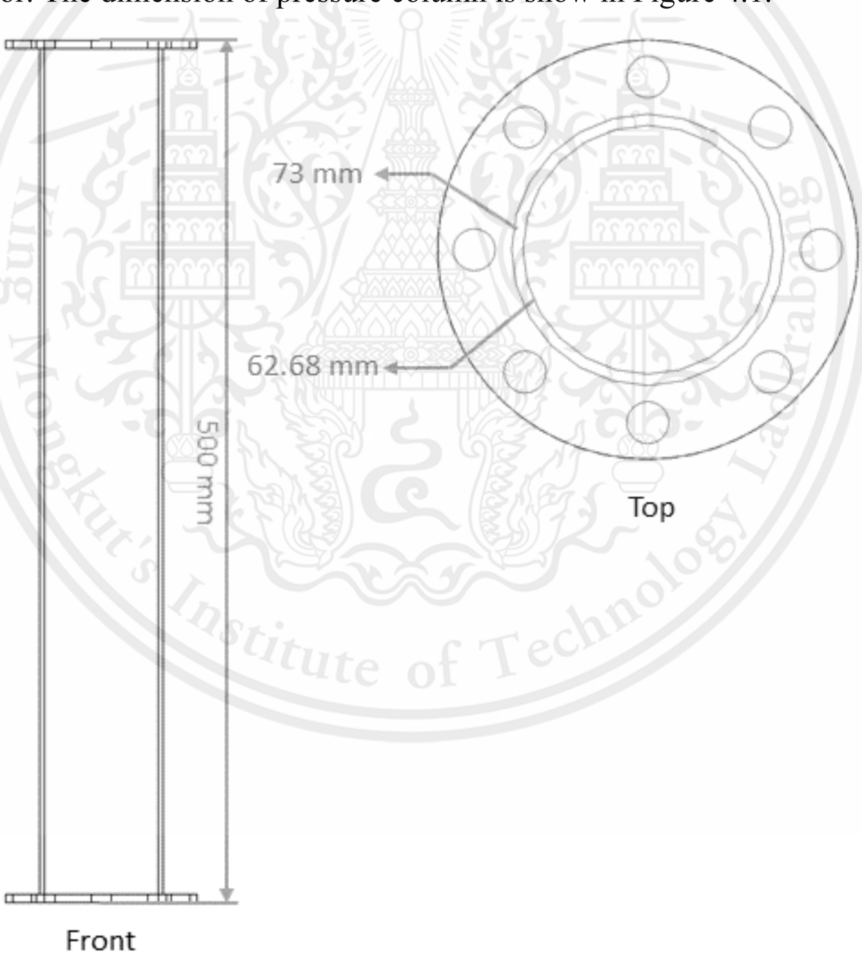

Figure 4.1: Dimension of column body.

4.1.2 Head design

Type of head is selected as ellipsoidal head with crown radius 36.5 mm and 100 mm length since it is suitable for operating pressure and widely used. The thickness of ellipsoidal head are equal to 5.16 mm. At the top of head, diameter of inlet hole is equal to 3/8 inch. The dimension of head is shown in Figure 4.2.

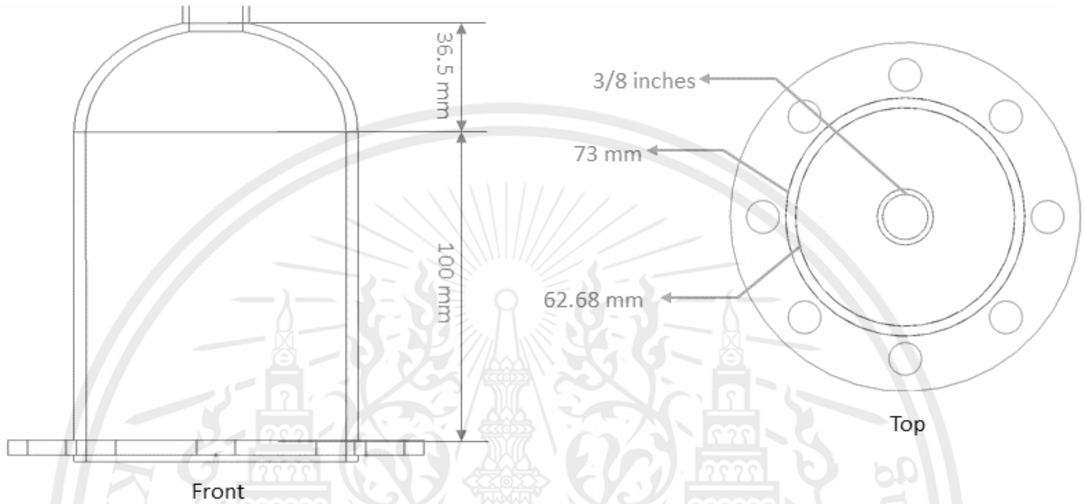

Figure 4.2: Dimension of ellipsoidal head.

The simulation of fluid flow at entrance region is simulated. The boundary condition for simulation are pressure 10 bar and inlet flowrate 10 L/min, the results revealed that there is a vortex near the top of the head as shown in Figure 4.3. Hence, the bottom of head is designed to allow fluid fully developed before contact with adsorbent.

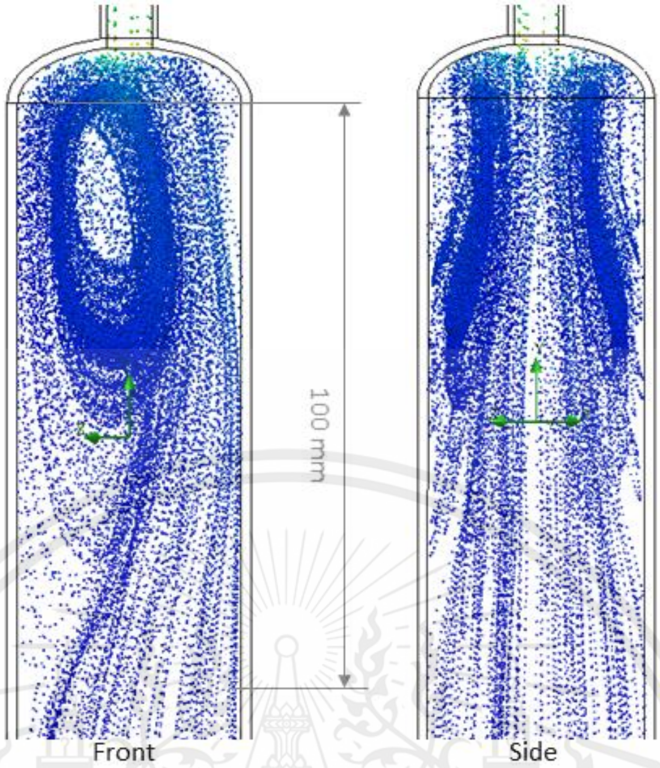

Figure 4.3: Flow simulation for find suitable length of cylindrical part.

To reduce the length of bottom part of head, distributor is suggested to add into a head. A honeycomb distributor which add to center of cylindrical section of head is shown in Figure 4.4.

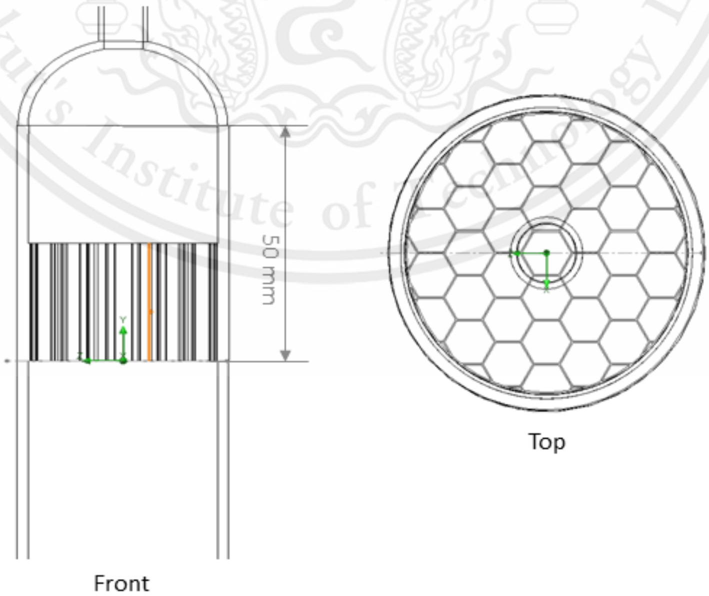

Figure 4.4: Honeycomb distributor

The simulation of fluid flow inside of head after installed distributor is performed, honeycomb distributor made inlet fluid more turbulent than without distributor as shown in Figure 4.5. Hence, head without distributor is better to let fluid fully developed than head with distributor.

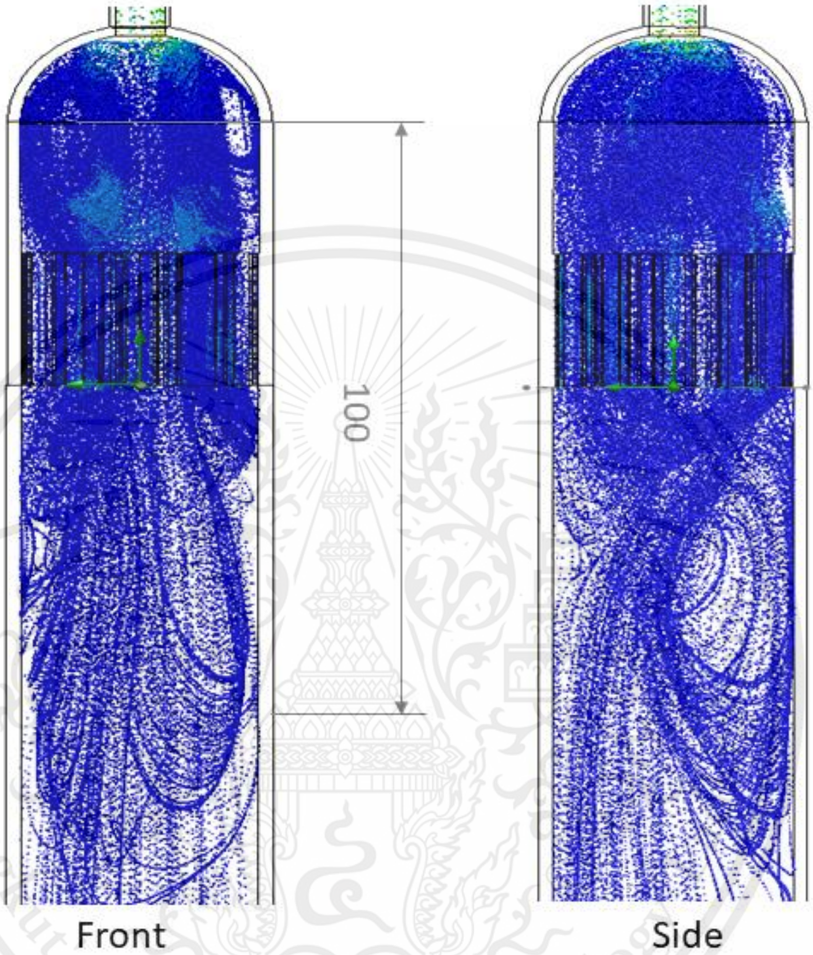

Figure 4.5: Fluid flow simulation with distributor.

4.1.3 Base design

Base of pressure column using stainless steel 304 as material to prevent rust and long life used. The dimension of base in term of millimeter are show Figure 4.6. After manufacturing the base and pressure column are shown in Figure 4.7.

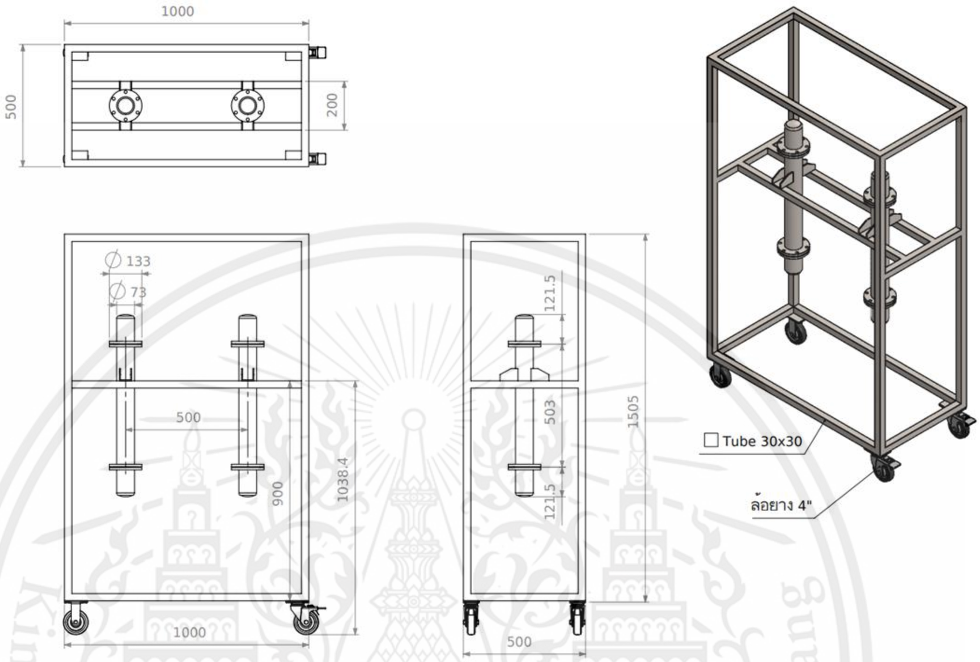

Figure 4.6: The dimension of pressure column and base.

Figure 4.7: Pressure column and base.

4.2 Piping and instrument diagram (P&ID) of Laboratory Scale Pressure Swing Adsorption Column.

The Piping and instrument diagram of laboratory scale pressure swing adsorption column is shown in Figure 4.8. From the figure, pressure of both CO_2 from tank and air from compressed line is regulated by CO_2 regulator and air regulator, respectively. The CO_2 and compressed air are pass through check valve (CV9, CV10) and mixed at three ways fitting. The flow rate of mixed gas is control by flow meter (FT) and control valve (13). The flow rate of mixed gas is using between 1 to 10 L/min. The concentration of CO_2 inlet is measured by CO_2 sensor (AT1). Then mixed gas is flow to one of adsorption column through a switching valve (S1 or S2) which is depended on operator. The pressure in the columns is measured by pressure transmitter (PT) and it is controlled by pressure controller (PIC), motor actuator (M) and control valves (7,8). The outlet concentration of CO_2 is measured by CO_2 sensor (AT2) to compare with inlet concentration. When one of columns are fully adsorb, solenoid valves (S1 to S6) are automatic switching on-off by Arduino automatic control system to switch mixed gas inlet to another column. To regenerate the adsorbate, the fully adsorbed bed is desorbed by outlet gas from another column at atmospheric pressure.

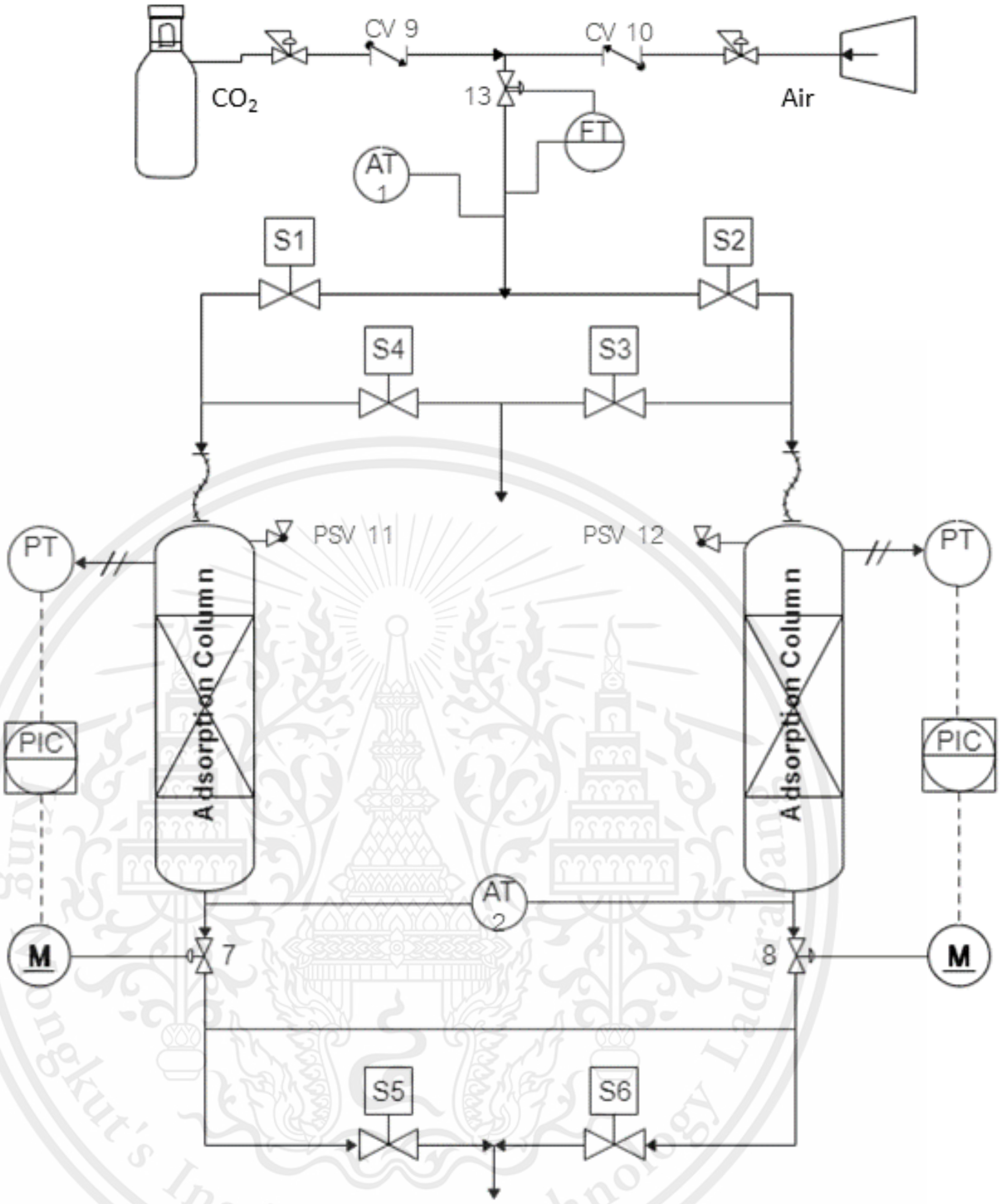

Figure 4.8: P&ID of Laboratory Scale Pressure Swing Adsorption Column.

There are three importance systems for instrumentation design, i.e., volumetric flow rate control loop, automatic switching inlet of fluid system and pressure control loop.

4.2.2 Flow control loop

Volumetric flow rate of mixed gas is control by the control loop in Figure 4.9. This control loop is consisting of flow meter (FT) and control valve (13).

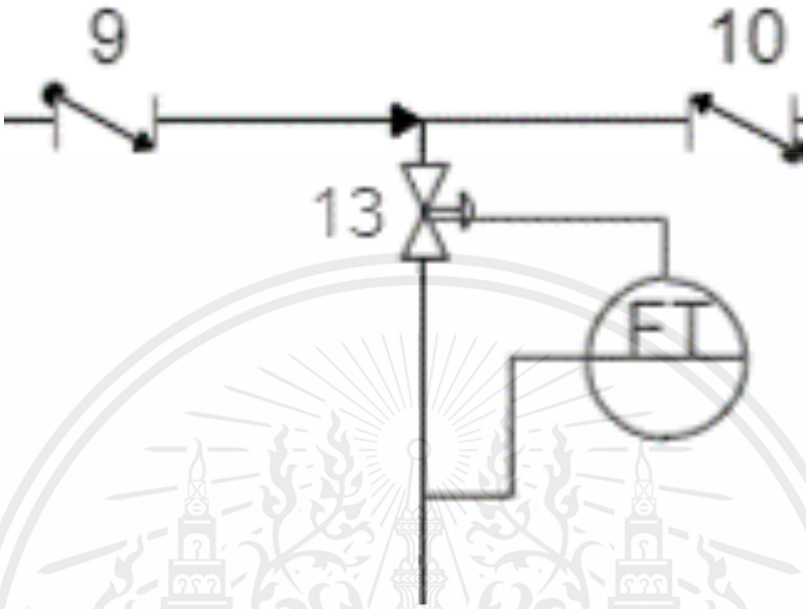

Figure 4.9: Flow control loop of inlet gas.

4.2.3 Automatic switching inlet system

Instrument of automatic switching inlet of fluid system is trigged when first column fully adsorbed to switch inlet to another column which is including solenoid valves (S1 to S4), fitting and Arduino board which shown in Figure 4.10.

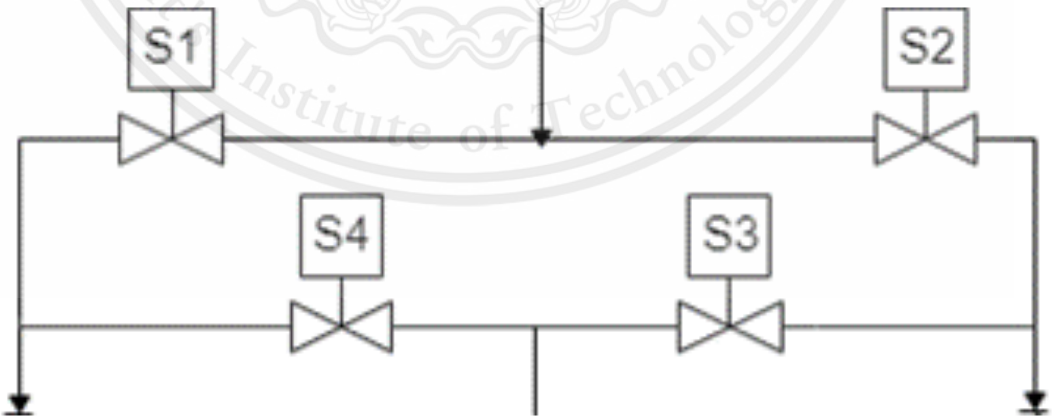

Figure 4.10: Automatic switching inlet of fluid system.

4.2.4 Pressure control loop

The pressure control loop is shown in Figure 4.11, which consist of pressure transmitter (PT), pressure controller (PIC), motor actuator (M), and control valves (8).

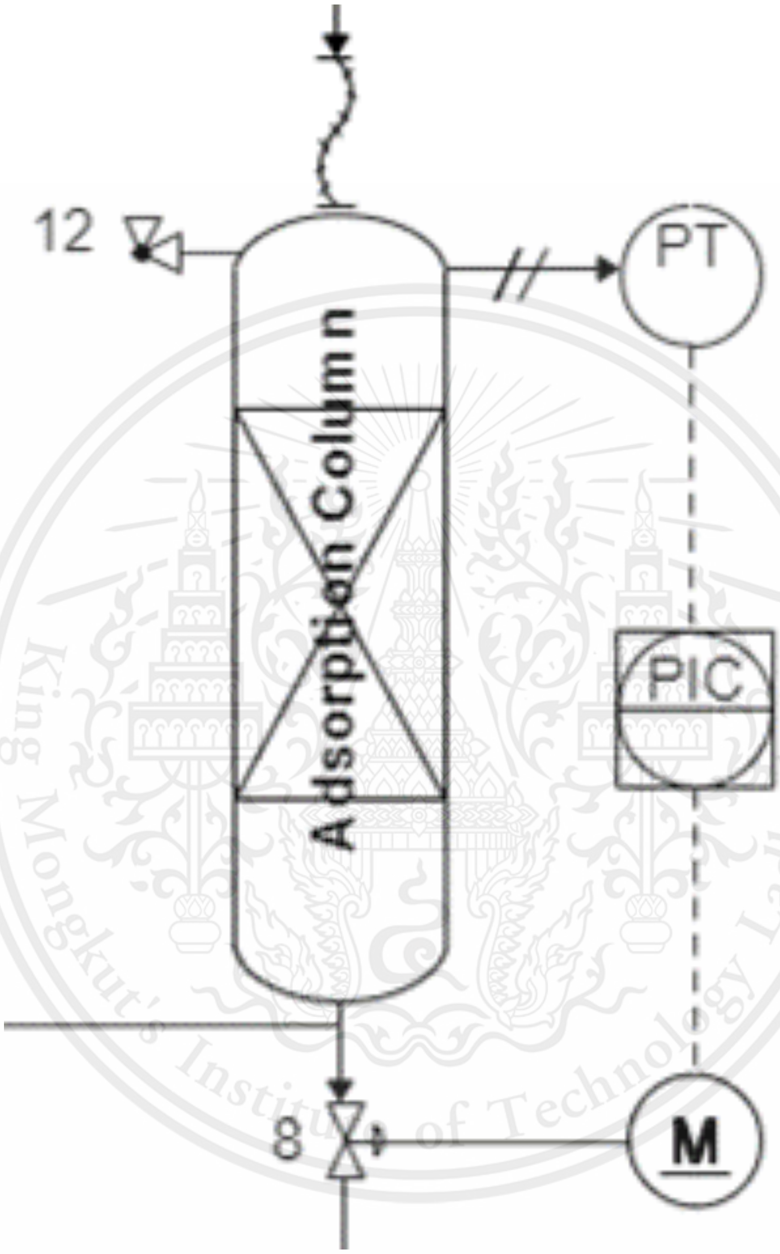

Figure 4.11: Pressure control loop of pressure column.

4.3 Instrumentation

This part is discussed about each instrument of control loops and control system which is suitable with operating condition.

4.3.1 Pressure transmitter (PT)

Pressure transmitter are selected by operating pressure, type of fluid and input power. Selected pressure transmitter are Gravity 3-pin interface which is shown in Figure 4.12. It supports 5 V input and 0.5-4.5 V almost linear output. It is compatible with multiple Arduino controllers.

Figure 4.12: Gravity 3-pin pressure transmitter[25].

The detail specification and operating condition of selected pressure transmitter are shown in Table 4.1.

Table 4.1: Specification of Gravity 3-pin pressure transmitter.

Specification	
Type of fluid	Gas and liquid without corrosion
Pressure measurement (MPa)	0-1.6
Input voltage (V)	5 DC
Output voltage (V)	0.5-4
Operating temperature (°C)	-20-85
Measurement Accuracy (%)	0.5-1
Response time (ms)	< 2
Damaged pressure (mPa)	3.0

4.3.2 Pressure controller (PIC)

Pressure controller of this study is building based on Arduino which including Arduino board UNO R3 board, LCD 16x2 monitor, and switch button. To build pressure controller each component are wiring as Figure 4.13.

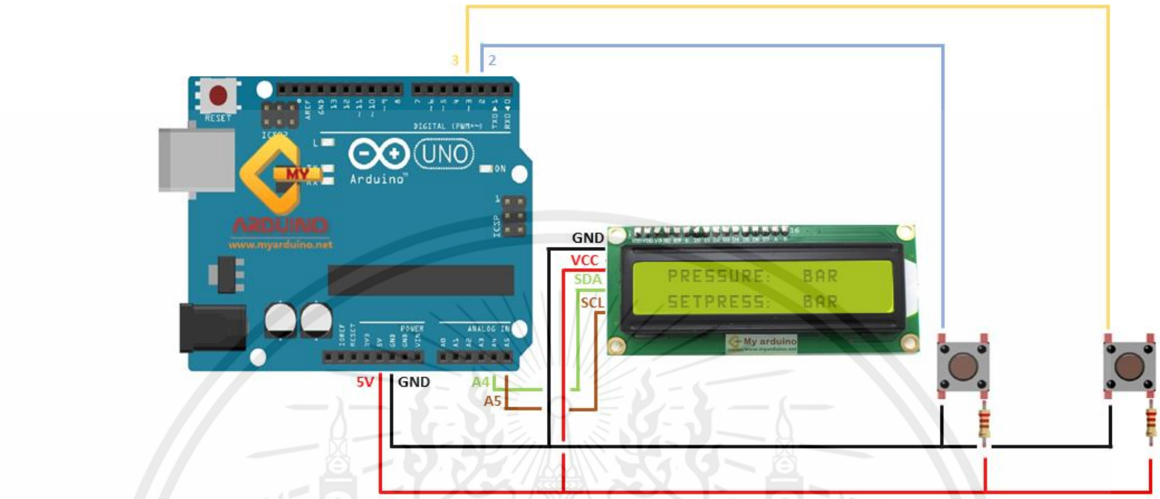

Figure 4.13: Pressure controller wiring.

To measured and controlled pressure, pressure controller are wiring to pressure transmitter as Figure 4.14. To avoid error of pressure transmitter ground, ground wire must be connected to ground of Arduino board.

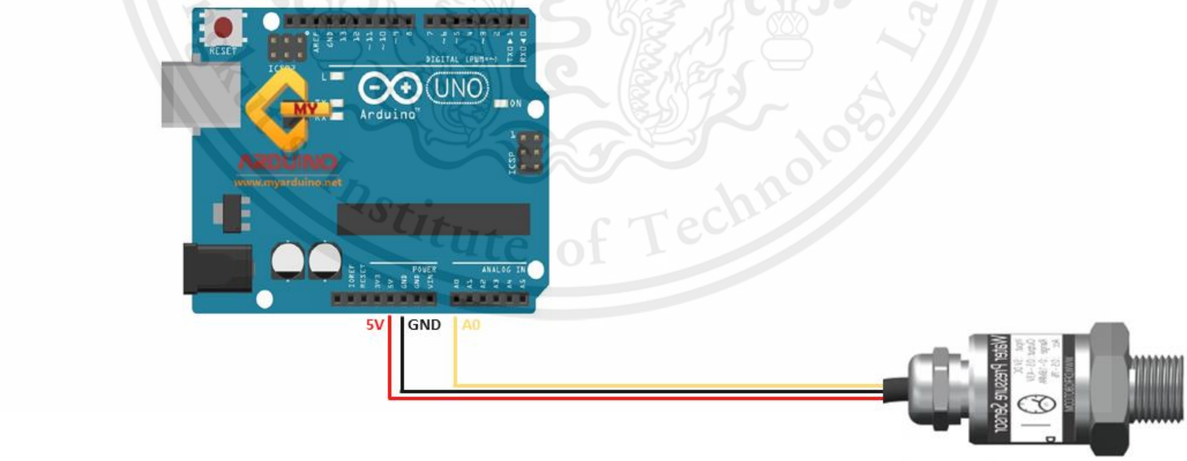

Figure 4.14: Wiring of pressure controller and pressure transmitter.

After connected pressure controller and pressure transmitter, code of pressure controller is coding to Arduino board to measure and compare pressure in the column with setpoint pressure which codes are in appendix C. Working flow chart of pressure controller is shown in Figure 4.15.

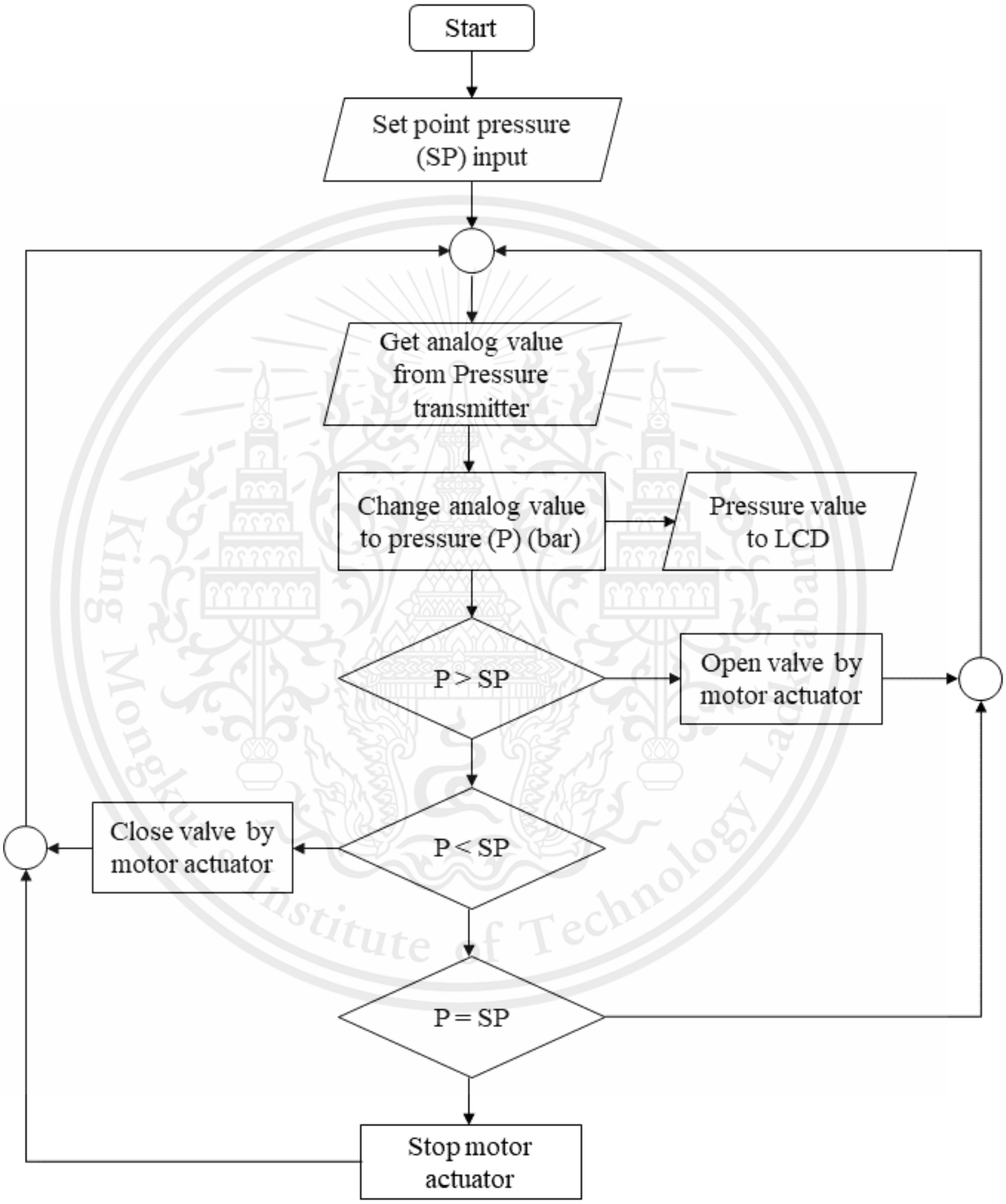

Figure 4.15: Flow chart of pressure controller

To measure pressure by pressure transmitter, it must be calibrated of pressure and voltage output to coding before usage. The calibration curve of pressure transmitter is shown in Figure 4.16 which calibration data is in appendix B.

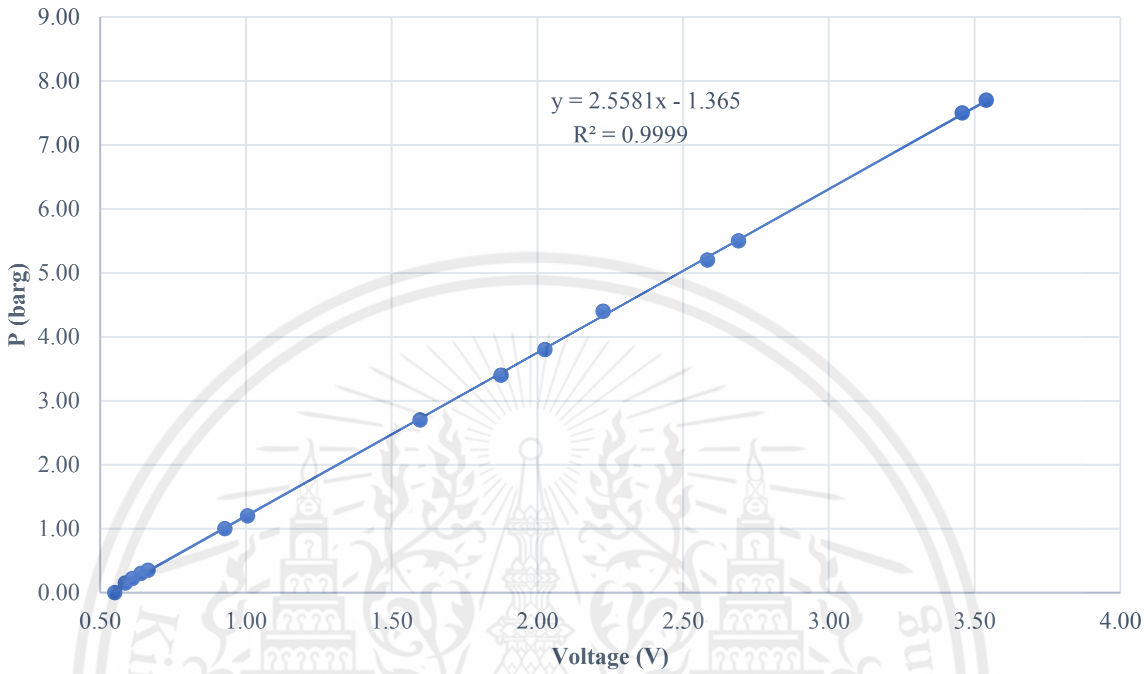

Figure 4.16: Calibration curve of pressure transmitter.

4.3.3 Motor actuator (M)

Servo motor is selected as actuator because of rotating direction and rotating velocity could be adjustable. Servo motor should be selected by suitable torque which provided to control valve. Servo motor is connected to Arduino board as Figure 4.17. To avoid backward current, suggestion is provided input current from external source.

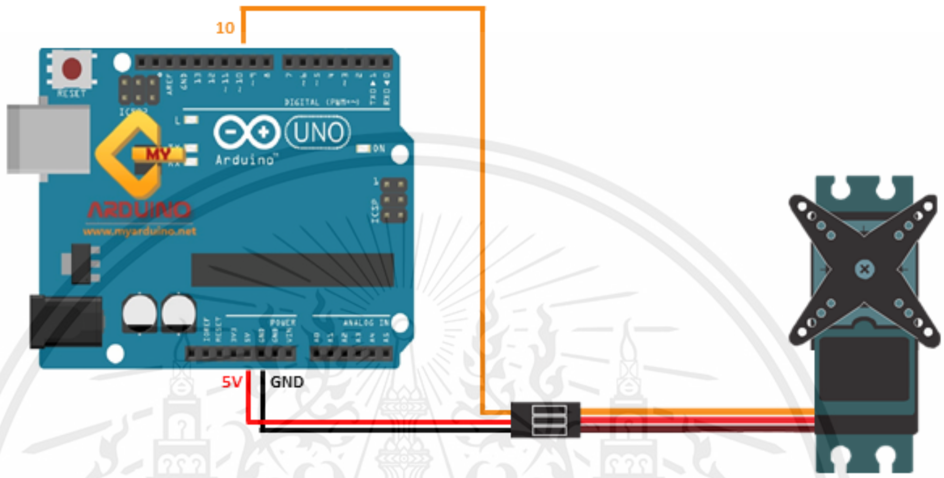

Figure 4.17: Wiring of servo motor and Arduino board.

MG996R Servo Motor 360 degrees is used for this study based on suitable torque to control valve. The specifications of this servo motor are shown in Table 4.2.

Table 4.2: Specification of MG996R Servo Motor 360 degrees.

Specification	
Operating speed (RPM)	58.8 (No load)
Torque (kg-cm)	13 (at 4.8V)
Operation voltage (V)	4.8-7.2
Gear type	Metal

4.3.4 Control valve (CV)

To control pressure in the column and inlet flow rate of mixed gas, final control element is select as needle valves. Because of needle valve is suitable to gas regulated and small operation system. Metallic body needle valve is having durability of high pressure. The disadvantage of needle valve is cannot completely block the flow, but to control pressure and volumetric flow rate this disadvantage is not concerned. Needle valve which is used in this study is SS-1RS4 Swagelok shown in Figure 4.18 and the specifications of this needle valve are shown in Table 4.3.

Figure 4.18: SS-1RS4 Swagelok needle valve[26].

Table 4.3: Specification of SS-1RS4 Swagelok needle valve[26].

Specification	
Body Material	316 stainless steel
Connection size	1/4 in
Max Temperature with pressure rating	232°C @ 236 bar
Flow Pattern	Straight (2-way)
Pressure rating at room temperature	344 bars @ 37°C
Stem Tip Material	316 Stainless Steel

4.3.5 Solenoid valve

Solenoid valves are used for automatic on-off system. To operated solenoid valves, automatic switch call relay is used. Relay also used with Arduino board. Solenoid valve, relay, and Arduino board are wiring as Figure 4.19. Code of solenoid valve of this study is in appendix C.

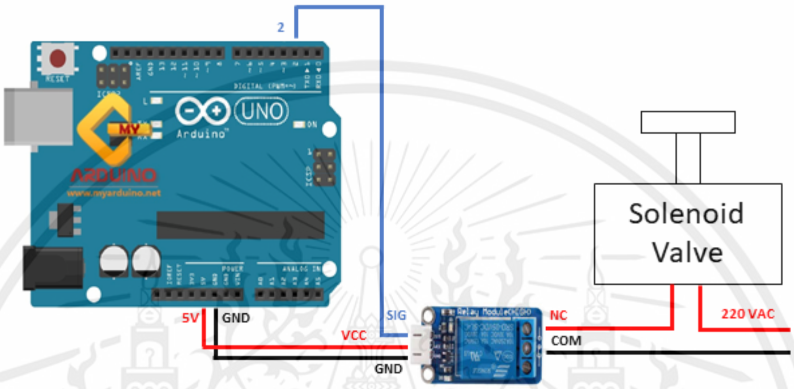

Figure 4.19: Wiring of Arduino board, relay and solenoid valve.

The SENYA electric Solenoid Valve 220V normally closed 1/4 inch is selected for this study figure and specification are shown in Figure 4.20 and Table 4.4, respectively.

Figure 4.20: SENYA electric Solenoid Valve 220V.

Table 4.4: Specification of SENYA electric Solenoid Valve 220V.

Specification	
Type of fluid	Water, air, oil
Power supply	220 V AC
Rated current (A)	0.1
Working pressure (bar)	16
Fluid temperature (°C)	0-80
Environment temperature (°C)	0-40
Operating mode	Normally closed
Material	Brass

CHAPTER V
CONCLUSION

This chapter is discussed about conclusion of this study and suggestion , how to develop system and further studied.

5.1 Conclusion

This study aim to design process, equipment and selected suitable instrument for laboratory scale pressure swing adsorption column. Process was design to operate at pressure 10 bars and volumetric flow rate at 1 to 10 L/min, the 2.5 inches stainless steel 304 sch 40 pipe was selected. The pipe length is 50 cm was chosen to get internal volume of 2.0 liters. From this design, it could withstand pressure 10 bar which is provide stress 21.2 N/mm^2 which is not over allowable stress in IS-2825 standard. Head of column is ellipsoidal head with thickness 5.16 mm and crown radius 36.5 mm which capable to withstand pressure at 10 bars. The cylindrical part of head with 100 mm length is added to allow fluid fully developed before contact with the adsorbent. The control system of this pressure swing adsorption is consisting of flow control loop, automatic inlet switching system and pressure control loop. In part of pressure control loop, pressure in the column is controlled by several instruments including pressure transmitter, pressure controller, motor actuator, and control valve as listed in section 4.3. Pressure controller is assembly base on Arduino UNO R3 board. Pressure transmitter is already tested and calibrated to operate at pressure 0 to 16 bar. In part of automatic switching inlet system, solenoid valve are used as automatic on-off valve supported by relay and Arduino which is already tested. The amount of required and available instrument are shown in Table 5.1

Table 5.1: The amount of required and available instrument.

Instrument	Amount	
	Required	Available
Pressure transmitter	2	1
Pressure controller		
- Arduino board	5	2
- LCD 16x2	2	2
- Button	4	2
Servo motor	2	1
Control valve	3	1
Solenoid valve	6	2
Pressure relief valve	2	0
CO_2 sensor	2	0
Flow meter	1	0
CO_2 regulator	1	0
Air regulator	1	1
Check valve	2	1

5.2 Suggestion

1. To operated high pressure system, safety devices must be considered such as relief valve, rupture disc, and etc.
2. Volumetric flow rate of CO_2 and air mixture should be measured by suitable flowmeter.
3. CO_2 sensor is suggested as MD62 Thermal Conductor CO_2 Gas Sensor.

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APPENDIX

Appendix A Calculation example

Tensile stress of column at

Operating pressure (p) =10 bar

Wall thickness (t) = 5.16 mm

Outside diameter (D) = 73 mm

$$f_p = \frac{pD}{2t}$$

$$f_p = \frac{(10bar)(73mm)(0.1N/mm^2)}{2(5.16mm)(1bar)}$$

$$f_p = 7.073\frac{N}{mm^2}$$

Then multiply by safety factor of IS-2825 standard.

$$f_p = 7.073\frac{N}{mm^2} \times 3$$

Allowable stress is

$$f_p = 21.22\frac{N}{mm^2}$$

Appendix B Calibration data

Table B.1: Calibration data of pressure transmitter.

Voltage (V)	Pressure (barg)
0.55	0.00
0.59	0.15
0.61	0.22
0.64	0.30
0.66	0.35
0.93	1.00
1.01	1.20
1.60	2.70
1.88	3.40
2.03	3.80
2.23	4.40
2.58	5.20
2.69	5.50
3.46	7.50
3.54	7.70

Voltage (V)	Pressure (barg)
0.55	0.00
0.79	0.56
0.88	0.80
0.96	1.00
1.35	2.01
1.74	2.99
1.93	3.50
2.11	3.96
2.39	4.69
2.52	5.03
2.72	5.56

Appendix C Coding

Pressure control code

```
#include <Servo.h>
#include<EEPROM.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);
Servo myservo;
const float OffSet = 0.483 ;
float V, P;
float setP = 0.00;
void setup()
{
  myservo.attach(10);
  Serial.begin(9600);
  lcd.begin
  lcd.backlight();
  pinMode(2, INPUT_PULLUP); //button1
  pinMode(3, INPUT_PULLUP); //button2
}
void loop()
{
  int b1 = digitalRead(2); //button decrease
  int b2 = digitalRead(3); //button increase
  delay(200);
  if (b1 == LOW) {
    setP += 0.5;
  }
  if (b2 == LOW) {
    setP -= 0.5;
  }
  V = analogRead(A0) * 5.00 / 1024;    //Sensor output voltage
  P = ((V * 2.6132) - 1.5442);         //Calculate water pressure
```

```
lcd.setCursor(9, 0);            //LCD แถวบน
lcd.print(setP);
lcd.setCursor(0, 0);            //LCD แถวบน
lcd.print("Setpoint:");
lcd.setCursor(13, 0);            //LCD แถวบน
lcd.print("bar");
lcd.setCursor(0, 1);            //LCD แถวล่าง
lcd.print("Pressure:     ");
lcd.setCursor(9, 1);            //LCD แถวล่าง
lcd.print(P);
lcd.setCursor(13, 1);            //LCD แถวล่าง
lcd.print("bar");
Serial.print("Voltage:");
Serial.print(V, 2);
Serial.println("V");
Serial.print(" Pressure:");
Serial.print(P, 2);
Serial.println(" bar");
Serial.println();
if (P > setP)
{
  myservo.writeMicroseconds(1400);   // สั่งให้ Servo หมุนตามเข็ม
  delay(100);
}
if (P == setP)
{
  myservo.writeMicroseconds(1450); // สั่งให้ Servo หยุด
  delay(100);
}
if (P < setP)
```

```
{ myservo.writeMicroseconds(1550); // สั่งให้ Servo หมุนทวนเข็ม
delay(100);}
 delay(100);
}
```

<u>Solenoid control code</u>

```
int V135 = 2;
int V246 = 3;// กำหนดขาใช้งาน
void setup()
{
 pinMode(V135, OUTPUT); // กำหนดขาทำหน้าที่ให้ขา 2 เป็น OUTPUT
 pinMode(V246, OUTPUT); // กำหนดขาทำหน้าที่ให้ขา 3 เป็น OUTPUT
 digitalWrite(V135, HIGH);
 digitalWrite(V246, HIGH);
 pinMode(4, INPUT_PULLUP); //button2
}
void loop()
{
 int b = digitalRead(4);
 if (b == LOW) {
  digitalWrite(V135, LOW); // Open Column1
  delay(100);
  digitalWrite(V246, HIGH); // Close Column2
  delay(200); }
 if (b == HIGH) {
  digitalWrite(V135, HIGH); // Close Column1
  delay(100);
  digitalWrite(V246, LOW); // Open Column2
  delay(200); }
```

BIOGRAHPY

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