DESIGN, CONSTRUCTION AND COMMISSIONING OF MICROALGAE PHOTOBIOREACTOR

AHMAD SHAFIQ BIN MOHAMAD

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Faculty of Chemical and Natural Resources Engineering
Universiti Malaysia Pahang

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LIST OF NOMENCLATURES

PBR	-	Photobioreactor
p	-	Biomass productivity
C_b	-	Cell concentration
D	-	Dilution rate
μ	-	Specific growth rate
μ_{max}	-	Maximum growth rate

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CHAPTER 1

INTRODUCTION

1.1 Background Of Study

Culture of microalgae in open ponds and raceway is well developed but only a few species can be maintained in traditional open systems that control contamination by using highly alkaline or saline selective environments. Although the term 'photobioreactor' has been applied to open algal ponds and channels, it is best reserved for devices that allow monoseptic culture which is fully isolated from a potentially contaminating environment. Fully closed photobioreactors provide opportunities for monoseptic culture of a greater variety of algae than is possible in open systems (E. Molina et al , 2001) .

Photobioreactors has been used widely in culturing microalgae. Although it has large potential, the design nowadays is taking too much space in open ponds and raceways. By this research, we will study the effect of column depth and mixing towards sunlight and photosynthesis of microalgae in the design model photobioreactor. This photobioreactor will simulate the concept of mixing in the open ponds as in upscale design. Previous research shows that the design of photobioreactors needs large space and area, for example open ponds and raceways.

In an optimal system where no other factors limit, the light availability determines the rate of photosynthesis and productivity. However, excessive light can be harmful and is known to produce a photoinhibitory response (Bannister, 1979;Aiba, 1982).We will also need to design an effective CO_2 sparger so that we can monitor and study the optimum carbon dioxide supply for microalgae's growth. The effect of this study will help to make an upscale design of photobioreactors that will save amount of space of lands or ponds.

1.2 Problem Statement

Designing a photobioreactor for microalgae needs many considerations to be put in to produce the optimum growth of the microalgae itself. In the previous research, large area needed to locate the photobioreactor. For the optimum growth of the microalgae several parameter has to be manipulated, that is:

a) Pressure of air sparged from the air compressor
b) Mixing in the airlift photobioreactor

1.3 Objectives

The objective of this research is to:

i. Design and construct microalgae photobioreactor.
ii. Test the airlift photobioreactor for flowrate and mixing by manipulating the pressure of air sparged through the airlift by using water.

1.4 Scopes

Scopes of the study were identified in order to achieve the research objectives. The construction and commissioning process have been done in Engineering Workshop FKKSA UMP. About 2 and a half month is taken to construct the photobioreactor. For this research, the scopes of study are:

i. Photobioreactor design
ii. Manipulated variable:
    - Mixing
    - Flowrate of air sparged.
iii. Relationship between the PBR design and manipulated variable.

1.5 Rationale and Significance

Microalgae photobioreactor has been used widely in advanced country to grow microalgae for their oils. This study will contribute and enhance the research on microalgae photobioreactor and thus the production of biodiesel from microalgae. Optimum pressure for air sparging into the PBR to make the liquid flow and to create turbulence for effective mixing will be determine.

LIST OF FIGURES

ABSTRACT

Oil can potentially be produced by microalgae which then can be converted into biodiesel. Although it has large potential, the design of reactor to grow microalgae nowadays is taking too much space in open ponds and raceways. The objective of this research is to design, construct and commission an airlift photobioreactor which will enable the operator to monitor and control mixing and the level of dissolved CO_2 in the medium and as well exposed it to sunlight for the microalgae to undergo photosynthesis. The construction comprises of two stages namely the first stage on the construction of the vertical airlift photobioreactor which will provide the flow, and the second stage on the construction of the horizontal solar receiver photobioreactor which will enable the microalgae to tap on the sunlight for photosynthesis. The work represented in this thesis concern only on the first stage. For this first stage, the most important factor is the mixing. We can manipulate it by varying the flowrate of air sparged through the airlift bioreactor. There were three series of methods that has been done to complete this research that is design, construct and commissioning process. The design photobioreactor has been used to construct the airlift bioreactor and the support structure. For the commissioning process, blue dye has been used to determine the dispersion pattern in the airlift photobioreactor. It was found that the blue dye was dispersed primarily because of the sparging of the air, even before the flowrate reaches turbulence which would have cause the mixing. After air has been sparged for first try at 2 psi, it takes 2 and a half minute for the dye to complete the cycle in the PBR. For 4 psi, 68 seconds, at 6 psi it takes 50 seconds and for the last at 8 psi, it takes 44 seconds for a complete cycle. Even though at 8 psi it takes shorter time to complete a cycle, overflow has been observed at the liquid-gas disengagement chamber. The optimum pressure of air sparged has been determined to be at 6 psi. The research has completely achieved all its objectives.

ABSTRAK

Minyak yang berpotensi dapat dihasilkan oleh mikroalga yang kemudiannya dapat ditukar menjadi biodiesel. Walaupun mempunyai potensi yang besar, desain reaktor untuk pertumbuhan mikroalga pada masa ini mengambil ruang yang terlalu besar di kolam terbuka. Tujuan dari penelitian ini adalah untuk mereka, membangun dan mengoperasi fotobioreaktor penaik udara yang akan membolehkan operator untuk memantau dan mengawal pencampuran dan kadar CO_2 terlarut dalam media dan juga terdedah kepada sinar matahari untuk membolehkan mikroalga menjalani fotosintesis. Pembinaan terdiri daripada dua tahap iaitu pada tahap pertama pembangunan fotobioreaktor penaik udara menegak yang akan memberikan aliran, dan tahap kedua pada pembangunan fotobioreaktor penerima suria mendatar yang akan membolehkan mikroalga untuk terdedah pada cahaya matahari untuk proses fotosintesis. Tesis ini hanya merangkumi tahap yang pertama. Untuk tahap pertama ini, faktor yang paling penting adalah pengadukan. Kita dapat memanipulasi parameter ini dengan memvariasikan laju aliran udara yang disembur melalui bioreaktor penaik udara. Ada tiga rangkaian kaedah yang telah dilakukan untuk menyelesaikan kajian ini iaitu rekabentuk, proses pembinaan dan pengoperasian. Rekaan fotobioreaktor telah digunakan untuk membina bioreaktor penaik udara dan struktur penyokong. Untuk proses pengoperasian, pewarna biru telah digunakan untuk menentukan pola penyebaran di fotobioreaktor penaik udara. Didapati bahawa pewarna biru itu tersebar terutamanya kerana semburan udara, bahkan sebelum mencapai laju aliran yang akan menyebabkan pengadukan. Setelah udara disembur, untuk percubaan pertama pada 2 psi, diperlukan dua minit dan tiga puluh saat untuk pewarna biru melengkapkan kitaran di dalam fotobioreaktor tersebut. Untuk 4 psi, 68 saat diperlukan, manakala pada 6 psi, 50 saat diperlukan. Untuk yang terakhir pada 8 psi, 44 saat diperlukan untuk kitaran yang lengkap. Meskipun pada 8 psi waktu yang lebih singkat

diperlukan untuk sebuah kitaran, limpahan pada bahagian pengasing gas dan cecair telah diamati. Tekanan udara optimum semburan telah ditetapkan sebanyak 6 psi. Kajian telah sepenuhnya mencapai semua tujuannya.

CHAPTER 2

LITERATURE REVIEW

2.1 Photobioreactor (PBR) Design

In an airlift driven tubular photobioreactor, the recirculation velocity of the culture and oxygen removal characteristics are closely linked. The culture performance is critically dependent on attaining an optimal design that provides the requisite flow and gas exchange. In addition, the photobioreactor geometry must maximize capture of sunlight while minimizing the land surface occupied (Molina *et al.*, 2001). Effects of tube length, flow velocity, the airlift column height, and the geometric configuration of the solar receiver on various performance parameters are discussed. A photobioreactor designed using the approach outlined is proved for culture of the microalga *Phaeodactylum tricornutum*. Figure 2.1 shows the example of microalgae photobioreactor that consists of airlift and its solar collector.

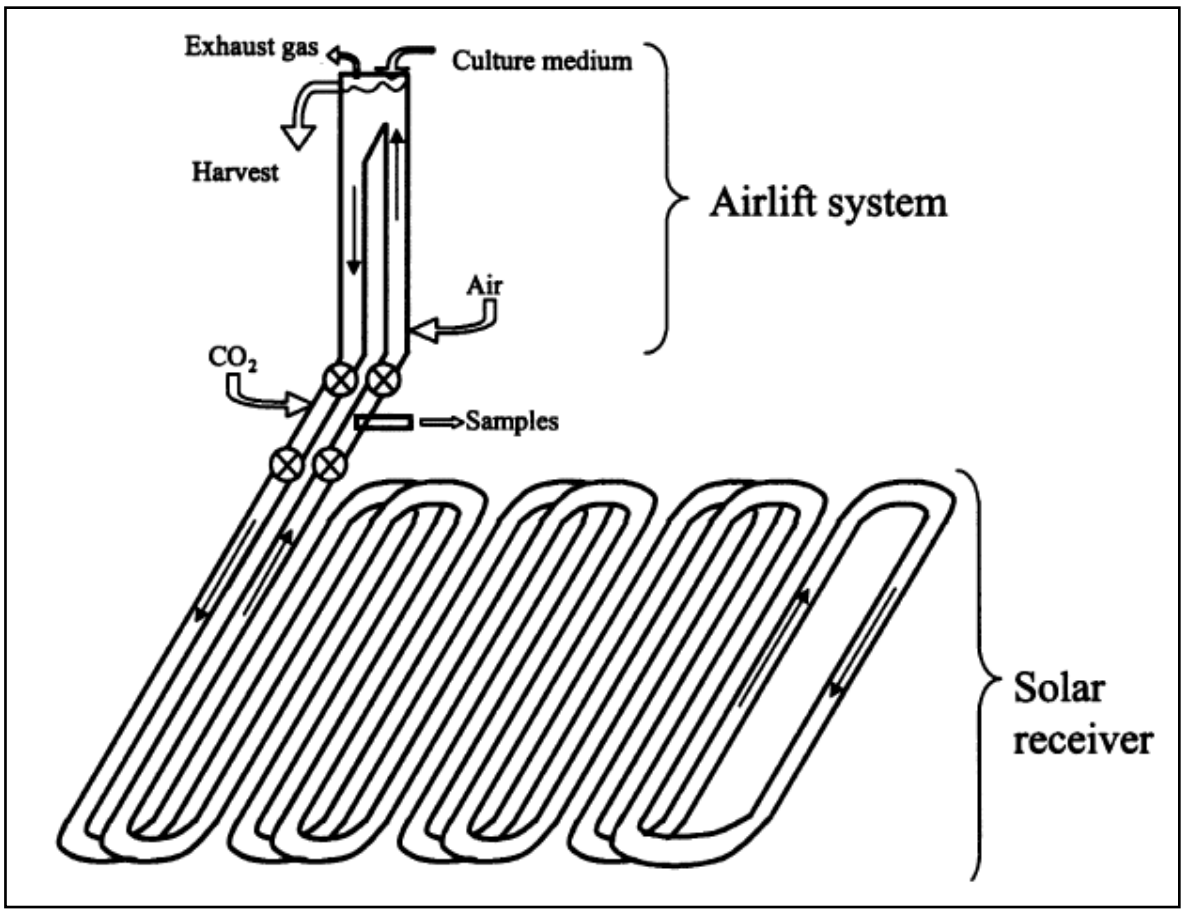

Fig. 2.1.: Example of Microalgae Photobioreactor Design

The airlift column circulates the culture through the solar collector tubing where most of the photosynthesis occurs. The oxygen produced by photosynthesis accumulates in the broth until the fluid returns to the airlift zone where the accumulated oxygen is stripped by air. A gas–liquid separator in the upper part of the airlift column prevents gas bubbles from recirculating into the solar collector. The solar loop is designed to efficiently collect the solar radiation, minimize resistance to flow, and occupy minimal area to reduce the demand for land. In addition, the diameter of the solar tubing is selected so that the volume of the dark zone (i.e. one with light intensity below saturation) is kept to a minimum. Also, the interchange of fluid between the light and the dark zones in the solar loop must be sufficiently rapid that element of fluid does not reside continuously in the dark zone for long (J.C Ogbanna., H. Tanaka, ,1997).

The airlift device must fulfill two needs: the circulation of fluid through the solar loop and stripping of oxygen from the broth. The volume of the broth in the airlift device needs to be small compared to the volume in the solar loops that cells spend as much time as possible in the relatively better illuminated loop. In this work, the riser and downcomer tubes of the airlift device were vertical extensions of the ends of the solar loop. The volume in the gas-liquid separator was minimized by reducing the spacing between the parallel walls (Figure 2.2) to the width of the riser (or the downcomer) tube.(Figure 2.1). The bottom of the separator was slanted at 60^0 relative to horizontal, so that the solid would not settle permanently.

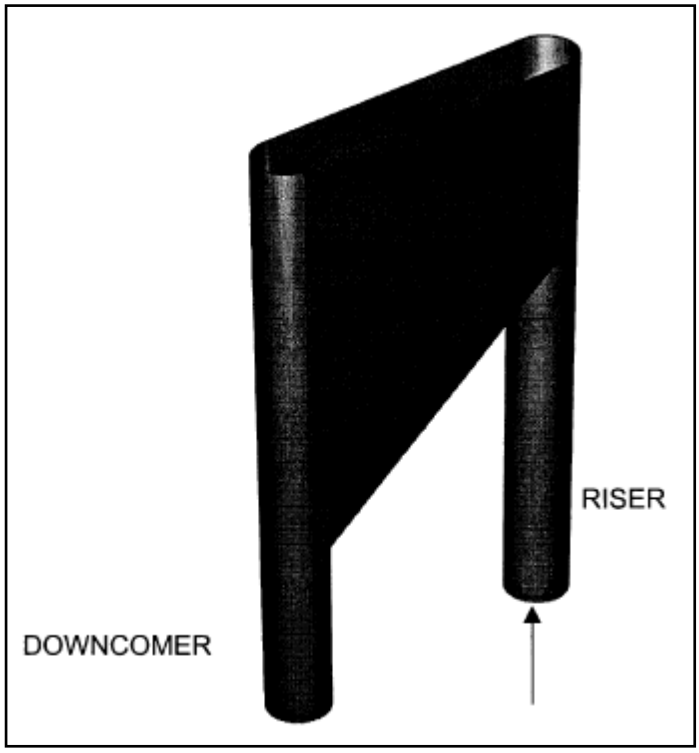

Figure 2.2: The gas-liquid separator

The head zone of the airlift column (Figure 2.1) was designed for almost complete separation of the gas from the liquid, before the broth recirculated into the solar collector. Complete disengagement of gas meant that the driving force for liquid circulation was the maximum attainable for any aeration rate in the airlift riser. For the disengagement of gas,

the distance between the entrance and the exit of the separator zone should be that smallest bubble can rise out of the fluid by the time it exits the separator and moves into the downcomer (Chisti and Moo-Young, 1993)

Availability and intensity of light are the major factors controlling productivity of photosynthetic cultures. In continuous culture as typically practiced for microalgae, the biomass productivity (p) is a function of the cell concentration (Cb) in the effluent and the dilution rate (D); thus, $p=DCb$. (C.G. Lee, B.Ø. Palsson, 1995). At steady state, the dilution rate equals the specific growth rate (μ) which is governed by the amount of light, the rate controlling factor. Generally, μ increases with increasing irradiance, reaching a maximum value, $\boldsymbol{\mu}_{max}$. Further increase in irradiance may actually inhibit growth - a phenomenon known as photoinhibition (E. Molina *et al.*, 1999).

An efficient large scale PBR has yet to be developed [Ogbanna *et al.*, 1997].This has left commercial production of algae to open ponds. Open ponds do not provide conditions necessary for high density algal biomass production because of diurnal and annual variation in light intensity and temperature. Chen (1996) states that enclosed PBRs have the following advantages over open pond production.

1. Better control of algal culture
2. Large surface-to-volume ratio
3. Better control of gas transfer
4. Reduction in evaporation of growth medium
5. More uniform temperature
6. Better protection from outside contamination
7. Higher algal cell densities are possible.

Removal of contaminates from air streams requires that the air be brought into contact with the growth medium (principally water) in the reactor area of the PBR. Air with contaminates may be moved over the surface of the growth medium, but this will

likely yield low gas transfer rates and will not enhance mixing of the algae-growth medium solution. Without mixing, the algae will tend to settle towards the lower portion of the PBR (Lee and Palsson, 1995). Mixing also reduces temperature gradients and enhances nutrient distribution in the solution. Mechanical mixing requires the addition of another system. Mixing the reactor solution with air containing contaminates (nutrients) can be done with perforated tubing or diffusers at the bottom of the reactor (Anderson *et al.*, 2002).

2.2 Microalgae and Its Potential

Microphytes are microscopic algae, typically found in freshwater and marine systems, and are often called microalgae. They are sunlight-driven cell factories that convert carbon dioxide to potential biofuels, foods, feeds and high-value bioactives. Microalgae, capable to perform photosynthesis, are important for life on earth; they produce approximately half of the atmospheric oxygen and use simultaneously the greenhouse gas carbon dioxide to grow photoautotrophically.

The biodiversity of microalgae is enormous and they represent an almost untapped resource. It has been estimated that about 200,000-800,000 species exist of which about 35,000 species are described. Over 15,000 novel compounds originating from algal biomass have been chemically determined (Cardozo *et al.* 2007). Most of these microalgae species produce unique products like carotenoids, antioxidants, fatty acids, enzymes, polymers, peptides, toxins and sterols. The chemical composition of microalgae is not an intrinsic constant factor but varies over a wide range, both depending on species and on cultivation conditions. It is possible to accumulate the desired products in microalgae to a large extend by changing environmental factors like temperature, illumination, pH, CO_2 supply, salt and nutrients.

Biodiesel demands are crucial in the advanced country, for example in the United States. Annually, the fuel consumed by transportation in the United States requires 0.53 billion m^3 of biodiesel. Other food sources, like oil crops, waste cooking oil and animal fat cannot realistically satisfy this demand. Only meeting the half of the demand will require unsustainably large cultivation area for major oil crops. This is showed in table 2.1.

Table 2.1 : Comparison of some sources of Biodiesel

Crop	Oil yield (L/ha)	Land area needed (M ha) [a]	Percent of existing US cropping area [a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1190	223	122
Jatropha	1892	140	77
Coconut	2689	99	54
Oil palm	5950	45	24
Microalgae [b]	136,900	2	1.1
Microalgae [c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.

Referring to table 2.1, microalgae appear to be the only source of biodiesel that has potential to completely displace fossil fuel. Unlike other oil crops, microalgae grow extremely rapid and many are exceedingly rich in oil. Microalgae commonly double their biomass within 24 hours. Biomass doubling times during exponential growth are commonly short as 3.5h. Oil content in microalgae can exceed 80% by weight of dry biomass (F.B.Metting, 1996, P. Spolaore *et al.*, 2006). Microalgae oil production depends on algal growth rate and the oil content of the biomass. Microalgae with high oil production are desired for producing biodiesel (Y. Chisti, 2007).

2.3 Comparison of Raceways and Tubular Photobioreactors

Table 2.2: Comparison of raceway and photobioreactor methods

Comparison of photobioreactor and raceway production methods		
Variable	Photobioreactor facility	Raceway ponds
Annual biomass production (kg)	100,000	100,000
Volumetric productivity (kg m^{-3} d^{-1})	1.535	0.117
Areal productivity (kg m^{-2} d^{-1})	0.048[a] 0.072[c]	0.035[b]
Biomass concentration in broth (kg m^{-3})	4.00	0.14
Dilution rate (d^{-1})	0.384	0.250
Area needed (m^2)	5681	7828
Oil yield (m^3 ha^{-1})	136.9[d] 58.7[e]	99.4[d] 42.6[e]
Annual CO_2 consumption (kg)	183,333	183,333
System geometry	132 parallel tubes/unit; 80 m long tubes; 0.06 m tube diameter	978 m^2/pond; 12 m wide, 82 m long, 0.30 m deep
Number of units	6	8

[a] Based on facility area.
[b] Based on actual pond area.
[c] Based on projected area of photobioreactor tubes.
[d] Based on 70% by wt oil in biomass.
[e] Based on 30% by wt oil in biomass.

Table 2.2 compares photobioreactor and raceway methods of producing microalgal biomass. This comparison is for an annual production level of 100 t of biomass in both cases. Both production methods consume an identical amount of carbon dioxide, if losses to atmosphere are disregarded. The production methods in Table 2.2 are compared for optimal combinations of biomass productivity and concentration that have been actually achieved in large-scale photobioreactor and raceways. Photobioreactors provide much greater yield per hectare compared with raceway ponds. This is because the volumetric biomass productivity of photobioreactors is more than 13-fold greater in comparison with

raceway ponds. Both raceway and photobioreactor production methods are technically feasible. Production facilities using photobioreactors and raceway units of dimensions similar to those in Table 2.2 have indeed been used extensively in commercial operations (Terry and Raymond, 1985; Molina Grima, 1999; Molina Grima et al., 1999; Tredici, 1999; Pulz, 2001; Lorenz and Cysewski, 2003; Spolaore *et al.*, 2006).

Figure 2.3: Microalgal recovered from the broth by filtration

Recovery of microalgal biomass from the broth is necessary for extracting the oil. Biomass is easily recovered from the broth by filtration (Fig. 5), centrifugation, and other means (Molina Grima *et al.*, 2003). Cost of biomass recovery can be significant. Biomass recovery from photobioreactor cultured broth costs only a fraction of the recovery cost for broth produced in raceways. This is because the typical biomass concentration that is produced in photobioreactors is nearly 30 times the biomass concentration that is generally obtained in raceways (Table 3). Thus, in comparison with raceway broth, much smaller volume of the photobioreactor broth needs to be processed to obtain a given quantity of biomass.

2.4 Acceptability of Microalgal Biodiesel

For user acceptance, microalgal biodiesel will need to comply with existing standards. In the United States the relevant standard is the ASTM Biodiesel Standard D 6751. In European Union, separate standards exist for biodiesel intended for vehicle use (Standard EN 14214) and for use as heating oil (Standard EN 14213) (Knothe, 2006).

Microalgal oils differ from most vegetable oils in being quite rich in polyunsaturated fatty acids with four or more double bonds (Belarbi *et al.*, 2000). For example, eicosapentaenoic acid (EPA, C20:5n-3; five double bonds) and docosahexaenoic acid (DHA, C22:6n-3; six double bonds) occur commonly in algal oils. Fatty acids and fatty acid methyl esters (FAME) with 4 and more double bonds are susceptible to oxidation during storage and this reduces their acceptability for use in biodiesel. Some vegetable oils also face this problem. For example, vegetable oils such as high oleic canola oil contain large quantities of linoleic acid (C18:2n-6; 2-double bonds) and linolenic acid (C18:3n-3; 3-double bonds). Although these fatty acids have much higher oxidative stability compared with DHA and EPA, the European Standard EN 14214 limits linolenic acid methyl ester content in biodiesel for vehicle use to 12% (mol).

No such limitation exists for biodiesel intended for use as heating oil, butacceptable biodiesel must meet other criteria relating to the extent of total unsaturation of the oil. Total unsaturation of an oil is indicated by its iodine value. Standards EN 14214 and EN 14213 require the iodine value of biodiesel to not exceed 120 and 130 g iodine/100 g biodiesel, respectively. Furthermore, both the European biodiesel standards limit the contents of FAME with four and more double bonds, to a maximum of 1% mol.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this section, we will discuss about the method that have been conducted during the research. This section will be divided into three categories that is the design, followed by construction and lastly the commissioning process.

3.2 Design of Airlift Photobioreactor

The design of airlift photobioreactor is considered of upper section and the bottom section. The upper section is consists of liquid-gas separator and degassing column. The bottom section is consists of series of parts that circulates to make the flow circulating in the airlift photobioreactor. The design with its dimension is drawn by using AutoCad 2007 software.

3.3 Construction of Airlift Photobioreactor

The fabrication process of the bioreactor is done by the help of Mr. Hairul Hisham from FKKSA. As the process involved cutting of , grinding and welding of metal and PVC material, training are provided before the construction is started. The work is done under supervision with the use of suitable personal protective equipment such as goggle, hand gloves and ear protection. The process is divided into two phases, the building of support structure and the building of the reactor.

3.3.1 Support Structure Construction

The support structure is build by using hollow carbon steel. The processes involve cutting, grinding and welding of the steel to make the desired shape according to the PBR structure. Stairs also have to build for the purpose of inserting water and nutrient from the top of the PBR. Picture diagram of the process making of support structure of the PBR is shown on Appendix A.

3.3.2 PBR Structure Construction

The material used in PBR construction is polyvinylchloride (PVC) plastic, consist of transparent and non-transparent (grey) PVC. Fittings also used to connect the series of pipe with diameter of 10 and 15cm. The fitting used are described as in Table 3.1. The process for making the PBR is also described in picture diagram in Appendix A.

Table 3.1: Type and quantity of fitting used

Type	Name	No of Units
	90° elbow (6")	2
	Reducing coupling	2
	Ball Valves	3
	90° elbow (4")	2
	Tee fitting (6")	1
	Tee Fitting (4")	2

3.4 Commissioning process of PBR

Commissioning process is used to evaluate whether the airlift PBR that has been constructed is working. To proceed with the process, the blue dye is used. PBR was connected to an air compressor with a pressure gauge to measure and control the pressure of air sparged in the PBR. 50 ml of blue dye is placed in a Schott bottle. Using water pipe, the PBR is filled with water until half of the degassing column is filled with water. The outlet and the air inlet valve have to be closed before the water is poured in.

5ml of blue dye is taken from Schott bottle using a syringe. Then, by using a hollow stainless steel rod, 5ml of blue dye is injected to the downcomer column. The air compressor is set up and the pressure is set as 2 psi for the first trial. The valve of air inlet is opened. Time for the blue dye to complete a cycle in the PBR is taken. The flow pattern and dispersion of blue dye is observed. The water is drained from the PBR after the blue dye has completely dispersed and the water is completely change color to blue. The commissioning process is repeated for pressure of 4, 6 and 8 psi.