DESIGN, CONSTRUCTION AND COMMISSIONING OF BIOREACTOR EXPERIMENTAL RIG TO MEASURE K_La OF OXYGEN IN NEWTONIAN FLUID

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DESIGN, CONSTRUCTION AND COMMISSIONING OF BIOREACTOR EXPERIMENTAL RIG TO MEASURE K_La OF OXYGEN IN NEWTONIAN FLUID

MUHAMMAD AFIQ BIN ARIFFIN

A project report submitted in partial fulfillment of the requirements for the award of the bachelor degree of Chemical Engineering (Biotechnology)

Faculty of Chemical and Natural Resources Engineering
Universiti Malaysia Pahang

APRIL 2010

"I hereby declare that this thesis entitled "Design, Construction and Commissioning of Bioreactor Experimental Rig to Measure k_La of Oxygen in Newtonian Fluid" is the result of my own research except as cited references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree".

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This research is dedicated to my beloved family for their faith and believed in me until now. They will always be my inspiration for me to achieve success in life.

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ABSTRACT

In this research, a bioreactor experimental rig was designed, constructed and finally commissioned in order to measure the k_La and ka_p of oxygen in Newtonian fluid. Distilled water was used as a sample of Newtonian fluid. The design of the rig was based on the standard geometry of a stirred tank reactor. Standard geometrical ratios of a stirred tank reactor with two Rushton disc turbine (RDT) impellers was used to design a system that can provide good mixing for a gas-liquid system. Two sets of RDT impellers were used to disperse the gas sparged by a ring sparger into the liquid content in the tank. The construction of this rig was done with the help of the Assistant Training Vocational Officer in the engineering workshop. The tank was built using transparent Polyvinyl chloride (PVC) while the two impellers and four equally spaced baffles were constructed using stainless steel. The effect of two variables, namely impeller speed and air flow rate on the volumetric transfer coefficient of oxygen from gas to the bulk liquid, k_La and on the mass transfer coefficient of oxygen from bulk liquid to the oxygen electrode, ka_p were studied. From the result, the increase in impeller speed and air flow rate will both increase the value of k_La and ka_p. The values of k_La and ka_p were predicted by fitting the mass transfer equation of oxygen to the experimental data by using sum of squared error minimization of the difference between the actual and predicted data using MATLAB programming.

ABSTRAK

Dalam kajian ini, sebuah bioreaktor rig eksperimen direka, dibina dan akhirnya ditugaskan untuk mengukur k_La dan ka_p oksigen dalam bendalir Newton. Air suling digunakan sebagai sampel bendalir Newton. Rekabentuk rig adalah berdasarkan geometri piawai sebuah tangki reactor berpengaduk. Nisbah geometri piawai untuk sebuah tangki reaktor berpengaduk dengan dua pengaduk turbin cakera Rushton (RDT) telah digunakan untuk membina sebuah sistem yang dapat menyediakan percampuran yang baik untuk satu sistem gas-cecair. Dua set pengaduk RDT digunakan untuk menyebarkan gas yang disemburkan oleh penyembur cincin ke dalam kandungan cecair dalam tangki. Pembinaan rig ini dilakukan dengan bantuan daripada Pegawai Pembantu Latihan Vokasional di bengkel kejuruteraan. Tangki dibina menggunakan PVC telus sedangkan dua pengaduk dan empat bafel sama ruang dibina menggunakan keluli tahan karat. Pengaruh dua pembolehubah iaitu kelajuan pengaduk dan kelajuan aliran udara terhadap pekali pemindahan isipadu oksigen dari gas ke cecair pukal, k_La dan pekali pemindahan jisim dari cecair pukal ke elektrod oksigen, ka_p telah dikaji. Hasilnya, dari kajian ini, didapati bahawa peningkatan kelajuan pengaduk dan kelajuan aliran udara kedua-duanya meningkatkan nilai k_La dan ka_p. Penganggaran nilai k_La dan ka_p dilakukan dengan cara menyesuaikan persamaan pemindahan jisim oksigen kepada data yang diperolehi melalui eksperimen dengan meminimumkan jumlah ralat ganda dua perbezaan diantara data-data sebenar dengan data-data yang telah dianggarkan menggunakan pengaturcaraan MATLAB.

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LIST OF ABBREVIATIONS AND SYMBOLS

ρ	-	Liquid density (kg/m^3)
μ	-	Liquid viscosity (Pa.s)
σ	-	Standard error
a	-	Specific surface of interface
B	-	Baffles width
C	-	Bottom clearance
C*	-	Saturated dissolved oxygen concentration (8.13 ppm)
C_L	-	Dissolved oxygen concentration in bulk liquid
C_p	-	Dissolved oxygen concentration at the probe
D_i	-	Impeller diameter
D_t	-	Tank diameter
DO	-	Dissolved oxygen
DOC	-	Dissolved oxygen concentration
DOT	-	Dissolved oxygen tension
F(t)	-	Function to be minimized
F_r	-	Froude number
g	-	Gravitational acceleration (9.81 m/s^2)
H_L	-	Liquid height
H_i	-	Height between impellers
H_t	-	Tank height
ka_p	-	Electrode mass transfer coefficient
k_La	-	Volumetric mass transfer coefficient
L	-	Length of impellers blade
N	-	Impeller speed
N_{CD}	-	Impeller speed for complete dispersion

N_F	-	Impeller speed for flooding
N_{po}	-	Ungassed power number
N_Q	-	Discharge coefficient
N_R	-	Impeller speed for recirculation
N_{Re}	-	Reynold's number
P_o	-	Ungassed power consumption
P_g	-	Gassed power consumption
PVC	-	Polyvinyl chloride
Q_g	-	Gas flow rate
R^2	-	Coefficient of determination of linear regression
RDT	-	Rushton disc turbine
t	-	time
W	-	Width of impellers blade
x1	-	Initial guess of ka_p
x2	-	Initial guess of k_La
YR(t)	-	Theoretical dissolved oxygen concentration at time t
YS(t)	-	Experimental dissolved oxygen concentration at time t

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Oxygen is a key factor for biological activity in a bioreactor where aerobic microorganisms presents. For example, in aerobic fermentation process, the supply of molecular oxygen to the surface of each microbial cell is the primary importance. The dissolved oxygen in the liquid medium is utilized for the microbial growth, product formation, and provision of energy through the respiration of the microorganisms. The study of transport process of oxygen in a gas-liquid system is important to determine how the dissolved oxygen is transferred to the liquid phase of the system. In such mixing phenomena, the study of oxygen transfer rate to the liquid medium is crucial for the optimization of the process.

Since oxygen is sparingly soluble in water, it may be the growth-limiting substrate in these fermentations. For bacteria, the critical oxygen concentration is about 5% to 10% of the saturated dissolved oxygen concentration, (DOC). Above this critical concentration, the oxygen concentration no longer limits growth (Shuler and Kargi, 2002). For optimum growth, it is therefore important to maintain the DOC above this critical level by sparging (bubbling gas through) the fermenter with air or pure oxygen. Of course, to be effective, the mass transfer rate from the gas bubbles to the liquid broth must equal or exceed the rate at which growing cells take up the oxygen.

Oxygen transfer from gas bubbles to the cells is usually limited by oxygen transfer through the liquid film surrounding the gas bubbles. The rate of oxygen transfer from the gas to the liquid phase is given by the equation

$$OTR = k_L a(C^* - C_L) \quad (1)$$

where $k_L a$ is volumetric oxygen transfer coefficient, C* is saturated dissolved oxygen concentration and C_L is actual dissolved oxygen concentration in the bulk liquid. Also, OTR is the term for oxygen transfer rate.

The kLa include two factors: (i) the mass transfer coefficient k_L which is mainly a function of the physical properties of the system and the temperature (O'Connor, 1955); and (ii) the specific surface of the interface ``a". Operation with smaller bubbles size is preferred as it can provide greater specific surface area of interface per unit volume. On the other hand, the concentration difference ($C^* - C_L$) is not significantly influenced by the physical system and it depends both on the oxygen concentration in the air inlet and the temperature of the operation (Levonen and Llaguno, 1984). C* decrease as the temperature of operation increases. Taking all these issues into consideration, it seems clear that it is necessary to know the values of $k_L a$ because it has been regarded as the most appropriate parameter to characterize oxygen transfer in a particular system (I. de Ory *et al*, 1999).

In University Malaysia Pahang, the students in Faculty of Chemical and Natural Resources Engineering study the effect of several variables on $k_L a$ value by utilizing a 10L fermenter that is available in the bioprocessing laboratory. The improper commission of the experiment by the undergraduate students has lead to the damage of the fermenter. This phenomenon has caused several difficulties to the postgraduate students and the fourth year students who want to use the fermenter for their research and fermentation process. In addition, sometimes the utilization of this fermenter during lab session is restricted because it has been booked or in used by the postgraduate student or the fourth year students who want to run their research. In order to encounter this problem, a new bioreactor experimental rig must be

designed and constructed to be utilized by the undergraduate students in order to measure the k_La value during their lab session.

The design and construction of this experimental rig has two main significances. The first one is for students comfort in study. Currently, the undergraduate students have to share the 10L fermenter available in the lab with the postgraduate students. This new rig will help the undergraduate students to study the k_La during their lab session without any intersection with the postgraduate research. In addition, the research done by the postgraduates and the fourth year students in their research project will not be interrupted by the lab session. Furthermore, the invention of this rig will enhance the future study on other operating variables that can affect the k_La value such as type of impeller, non-Newtonian fluids, the presence of alcohol, inorganic electrolytes and antifoaming agent. In other words, the design and construction of this bioreactor experimental rig will contribute to the research field and student comforts in study.

1.2 Problem Statement

Since the undergraduate students in Faculty of Chemical and Natural Resources Engineering are using the fermenter in the bioprocess laboratory to run their experiment to study the effect of several parameters on k_La value, they have to share the equipment with the postgraduate students who use the fermenter for fermentation process. Unfortunately, sometimes they cannot run their experiment because the device is in use or have been booked by the postgraduate students for their research.

Recently, faculty spent a lot of money for maintenance of the fermenter. This is due to the improper commissioning of the fermenter by undergraduate students which caused several damages to the device. This is such a waste of money. Besides, the fermenter will be unavailable to be used by the postgraduate students

because of maintenance. This incident will disturb the progress of the postgraduate research and result in the alteration of the lab session schedule.

In order to design a new rig for experimental studies, there are several problems need to be considered about the oxygen transport phenomena in the process. Firstly, the mass transfer of oxygen in the process will encounter several barriers. These barriers need to be reduced by appropriate geometrical design of the rig in order to provide excellent gas-liquid mixing.

For any fermentation process to be conducted, it is necessary to determine the volumetric mass transfer coefficient (k_La) of oxygen value in order to study the oxygen transfer characterization in the liquid medium for the optimization of the process. The k_La value for oxygen is influenced by several operating variables such as intensity of agitation and the aeration rate. Thus, it is necessary to determine the effect of these operating variables on the k_La value prior to any fermentation process.

1.3 Objectives

The purpose of doing this study is to achieve following objectives:

1) To design and construct a bioreactor experimental rig that can enhance gas-liquid mixing for transport process of oxygen in Newtonian fluids in order to be utilized by undergraduate students in their experiments for the determination of k_La value during lab session.

2) To study the effect of air flow rate and impeller speed on k_La and ka_p value for oxygen in Newtonian fluids.

1.4 Scopes of Study

In order to achieve the objectives of this project, the following studies will be carried out:

1) Theory of oxygen transfer process.
2) Standard geometrical design for a stirred tank reactor.
   - Standard geometrical design of stirred tank
   - Standard geometrical impeller design
   - Liquid flow patterns
   - Turbulence
3) Power consumption in stirred tank
   - Single Newtonian liquid
   - Reduced power consumption in aerated tank
   - Gas flow patterns
4) Operation variables affecting k_La and ka_p value.
   - Impeller speed
   - Air flow rate
5) Methods to determine volumetric mass transfer (k_La) of oxygen.
   - Static gassing out and other methods (Experimental)
   - Sum squared error minimization analysis (MATLAB)

CHAPTER 2

LITERATURE REVIEW

2.1 Theory of Oxygen Transfer Process.

Most industrial microbial processes are aerobic, and are mostly carried out in aqueous medium containing salts and organic substances; usually these broths are viscous, showing a non-Newtonian behavior. In these processes, oxygen is an important nutrient that is used by microorganisms for growth, maintenance and metabolite production, and scarcity of oxygen affects the process performance (Garcia-Ochoa *et al*., 2000a; Calik *et al*., 2004; Liu *et al*., 2006a). Therefore, it is important to ensure an adequate delivery of oxygen from a gas stream to the culture broth.

In many chemical and biochemical reaction, aeration is needed to supply oxygen that will be consumed in the particular reaction pathways. The oxygen can be supply to the system by means of air compressor or sparging pure molecular oxygen. In aerobic fermentation process, the supply of molecular oxygen to the surface of each microbial cell is very crucial in order for the cell to absorb the oxygen molecule to be consumed. Before reaching the surface of the microbial cell, a transport process will occur along the pathway from the air bubbles through the liquid medium. For the high cell density culture, problem arises where the growth of the microbial cells is limited by oxygen availability in the liquid phase. The mass transfer process of molecular oxygen in this system will encounter many types of barriers.

In order to make the oxygen is available for the microorganism, it must be bring into contact with the liquid and then transferring the dissolved gas from the gas-liquid interface to the microorganisms. Rapid oxygen supply needs large surface area of contact between the gas and liquid to facilitate the dissolution and turbulence and finally mix the dissolved gas into the bulk of the fermentation. Figure 2.1 describes the transport process of oxygen graphically.

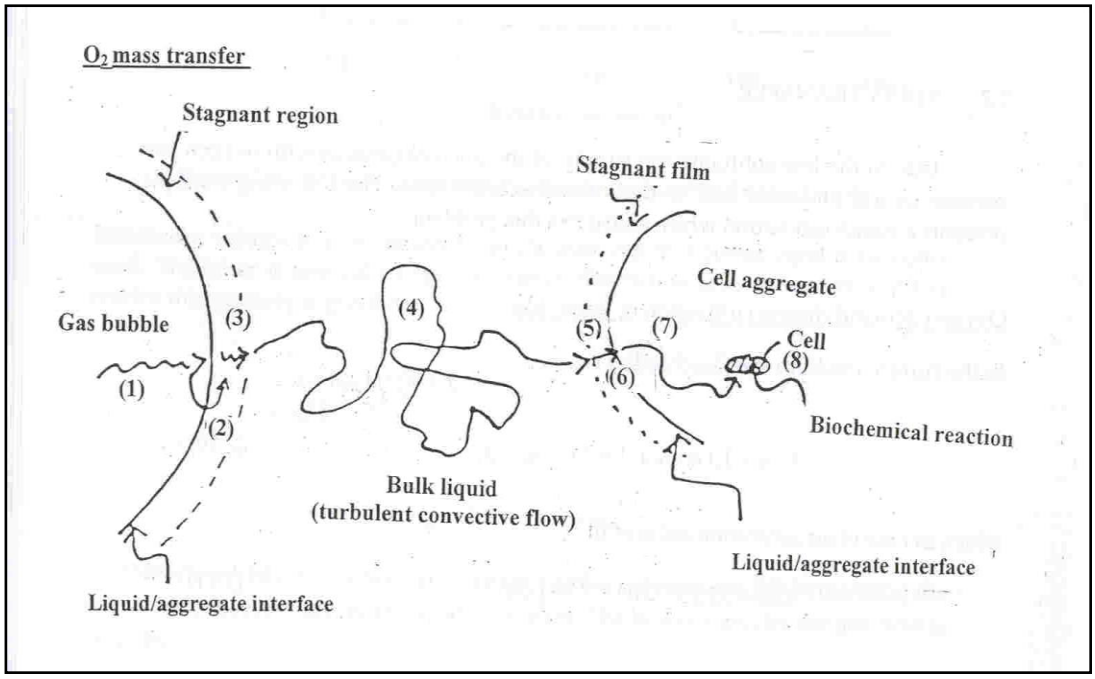


Figure 2.1 : Graphical view of oxygen transport process

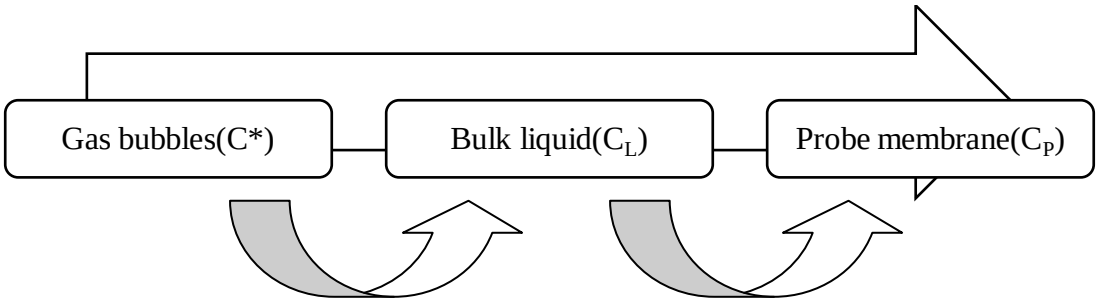
From the figure shown above, we notice that the mass transfer process will encounter several barriers:

1) Gas film resistance between bulk gas and gas-liquid interface
2) Interfacial resistance at the gas-liquid interface
3) Liquid film resistance between interface and bulk liquid phase
4) Liquid phase resistance for oxygen transfer to the liquid film surrounding a single cell
5) Liquid film resistance around the cells
6) Intracellular or intrapellet resistance (for microbial flocs or pellets)
7) Resistance due to consumption of oxygen inside the microbial cells

The sum of all resistance is equal to the overall resistance to transfer the oxygen into the cell. The magnitudes of individual resistance depend on the bubble

and liquid phase hydrodynamics, composition and rheological properties, densities, cell activities and gas- liquid interfacial phenomena. The sum of gas film, liquid film and interfacial resistances to oxygen transfer is reciprocal of overall oxygen transfer coefficient.

In this study, the mechanism of oxygen transfer is the same but the research is conducted using distilled water as a Newtonian fluid. Thus, the oxygen transport process can be illustrated by:



Theoretically, oxygen transfer process can be described as follow (Winkler, 1981) : The air is sparged into the distilled water content in the stirred tank. Oxygen from the gas bubbles will be transferred into the bulk liquid.

$$dC_L/dt = k_La(C^*-C_L) \quad (2)$$

Then, the dissolved oxygen from the bulk liquid will be transferred to the oxygen electrode's membrane.

$$dC_p/dt = ka_p(C_L-C_p) \quad (3)$$

After integration and rearrangement of equation, the theoretical dissolved oxygen concentration can be correlated by (Asis, 1990)

$$YR(t) = C^*-C^*[(ka_p.\exp(-k_La.t))/(ka_p-k_La) – (k_La.\exp(-ka_p.t))/(k_La-ka_p)] \quad (4)$$

where YR(t) = theoretical oxygen concentration at time t

C* = Saturated oxygen concentration in bulk liquid (8.13 ppm)

kap = electrode mass transfer coefficient of oxygen

kLa = volumetric mass transfer coefficient of oxygen

t = time

2.2 Standard Geometrical Design

2.2.1 Standard Geometrical Design of a Stirred Tank

In chemical processing, there is no such thing as a standard geometry stirred tank. However, most design information, from experimental studies and plant scale measurements, exist for the range of geometries given in table 2.2.1. Fig 2.2.1 shows the geometry of stirred tanks and defines the important dimensions. Many research has been carried out in flat bottomed tanks, despite the fact that the majority of industrial vessels have dished ends (ellipsoidal or torispherical) for the ease of fabrication and cleaning, and operation at elevated pressure.

Table 2.1 : Geometrical ratios of a stirred tank

	Geometric Ratio	Typical Range	Standard Geometry
liquid height	H / T	1-3	1
impeller dia	D / T	1/4 - 2/3	1/3
bottom clearance	C / T	1/4 - 1/2	1/3
bottom clearance	C / D	~1	1
baffle width	B / T	1/12 – 1/10	1/10

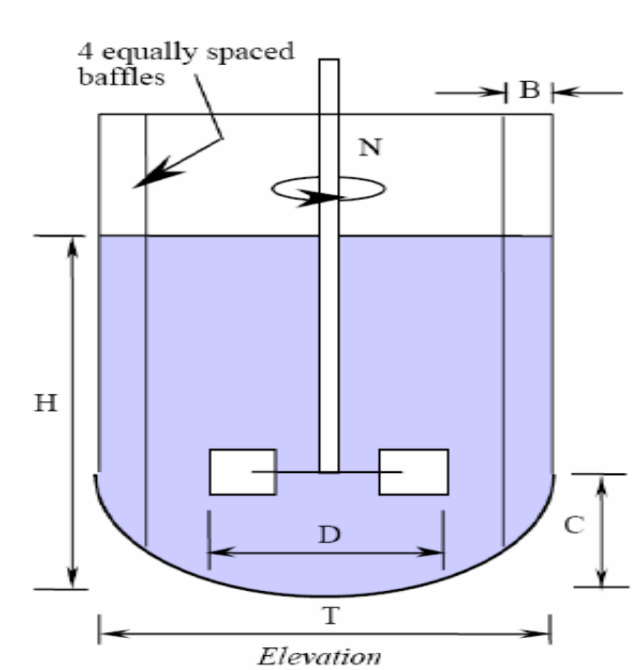


Figure 2.2 : Geometry of a stirred tank

The tank may be baffled or unbaffled. More effective mixing is obtained by placing baffles on the tank wall which generate large axial and radial velocities rather than a purely swirling flow. Full baffling may be achieved using four vertical baffles mounted radially, 90˚ apart; the baffles should extend to at least the free surface but often have a small clearance from the base of the vessel. For fluid mixing with dispersed solid particles, the baffles may be supported off the wall, leaving gap of ~ T/14. This is designed to prevent build-up of particles in the crevice between the baffles and the wall and to facilitate cleaning.

2.2.2 Standard Geometrical Impeller Design.

In low viscosity liquids, smaller diameter impellers (small D/T ratios) are able to generate flow in all parts of the tank at moderate power input. The common impeller types and its standard geometries are shown in figure 2.2 and can be classified according to the type of discharge flow produced. Figure 2.3 shows regular impellers dimension.

Table 2.2 : Impeller flow types and examples

Impeller flow type	Examples
Radial	Flat paddle, disc turbine
Axial	Marine propeller
Axial and radial mixed flow	Pitched-blade turbine, hydrofoil

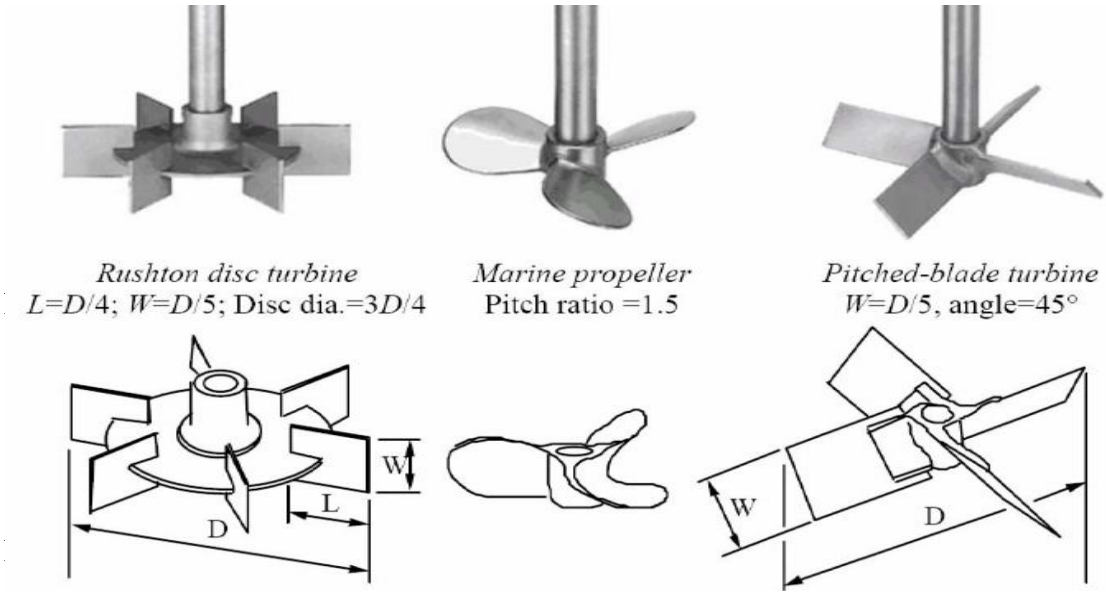


Figure 2.3 : Regular impeller dimension

With aspect ratio (H/T) greater than about 1.5, it is usual to have multiple impellers on the same shaft (each distance of ~ 1-2D apart) to give effective agitation throughout the tank volume. These impellers also have standard geometry design, e.g. a typical width to diameter ratio, W/D of 1/5 for Rushton disc turbine and mixed-flow pitched-blade turbines. A large number of literature measurements have been made on the standard Rushton disc turbine (6 bladed); formerly this design was regarded as one of the best multi-purpose agitators. However, recent research has shown that hydrofoil or pitched-blade impellers have certain advantages for specific low viscosity operation. Figure 2.4 shows some mixer selection chart for fluid processing.

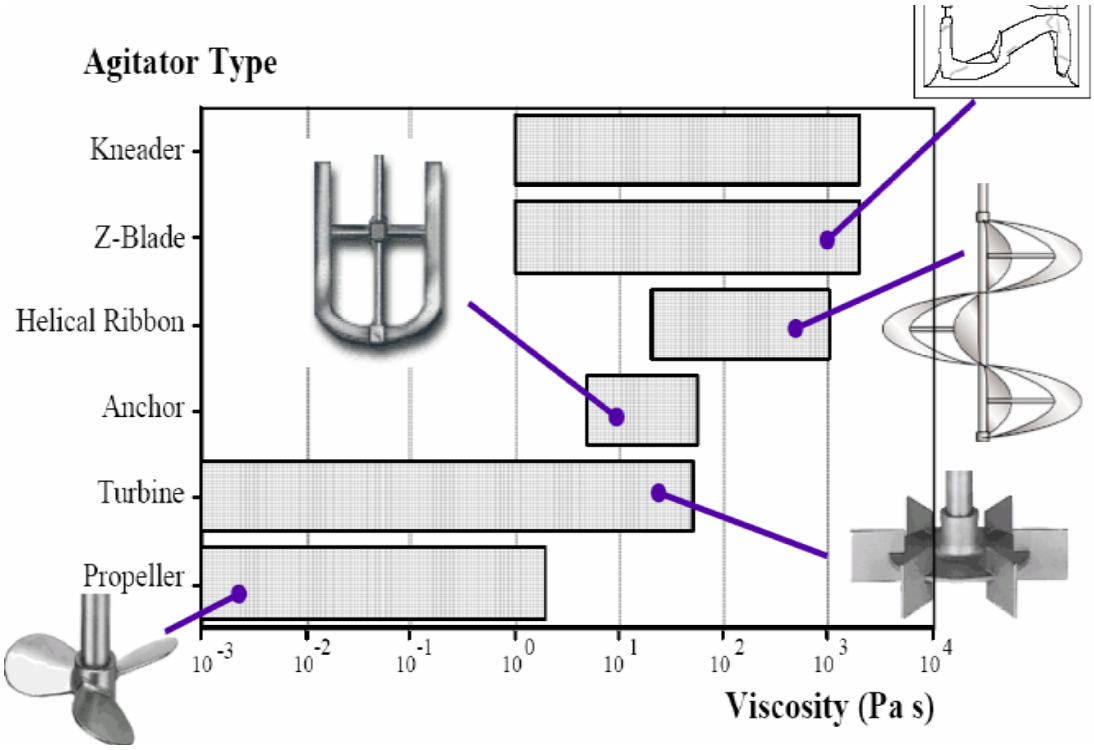


Figure 2.4 : Mixer selection chart for fluid processing

2.3 Liquid Flow Patterns

All small diameter impellers, rotating at high speed in low viscosity liquids, in unbaffled tanks produce a predominantly tangential swirling flow, with weaker, secondary vertical circulations. (Nagata, 1975) presents velocity profiles for a variety of impellers in unbaffled tanks and describes a theoretical model for the flow, consisting of a central solid body (forced vortex) region with an outer free vortex. In the central, solid body rotation there is no relative movement of fluid elements and hence no mixing. In the outer region, mixing is only achieved in the tangential direction. At higher impeller speeds, the surface vortex extends to the impeller blades and air is entrained. Consequently, unbaffled tanks are not efficient for blending operations. The use of an eccentric impeller improves blending efficiency by preventing the formation of the forced vortex and also introduces an additional problem that air is entrained from the free surface at low impeller speeds.

Baffling redirects the tangential and radial flow in the impeller discharge stream, generating strong vertical circulations. In baffled tanks, two distinct types of flow may be identified: 1) radial flow, as produced by the Rushton disc turbine; and, 2) axial flow, as produced by the marine impeller. Pitched-blade turbines generate a mixed flow with both axial and radial components in the discharge stream. These common flow patterns are illustrated in figure 2.5. In addition, there is evidence [Yianneskis *et al*., 1987] to show that these flows exhibit pseudo-periodicity due to shedding of trailing vortices from the impeller blades which means there is an element of unsteadiness in the flows.

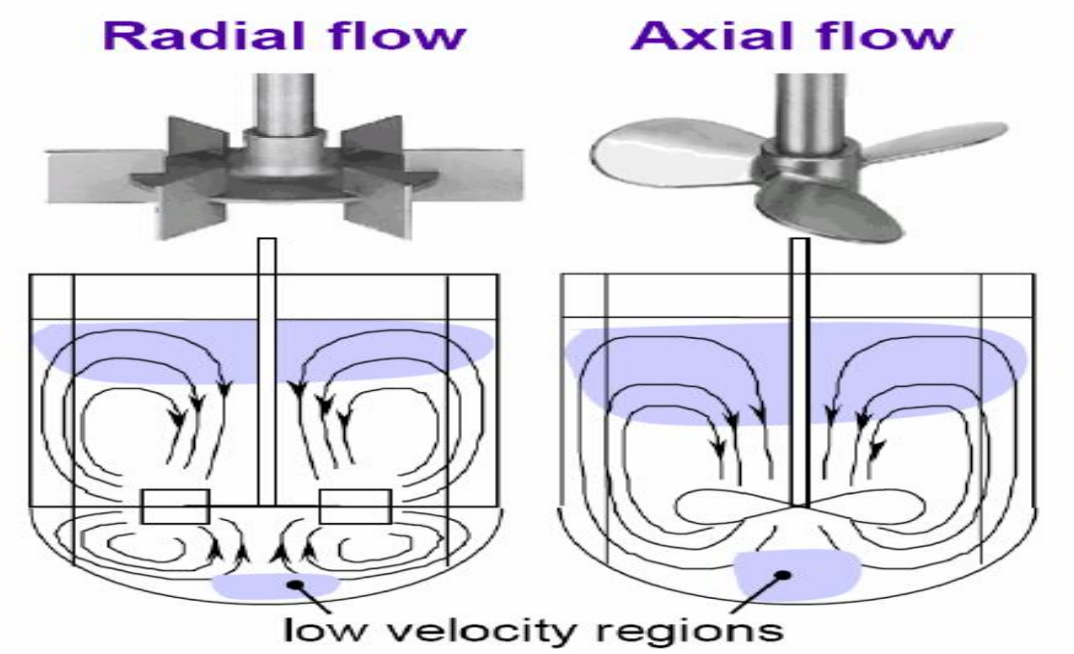


Figure 2.5 : Common flow patterns produced by impellers

More modern impeller designs like hydrofoil impeller give various combinations of axial and radial flow, depending on blade shape and pitch. In blending process, the impeller should produce a strong circulating flow but consume only small amount of power. In contrast, in gas-liquid or liquid-liquid dispersions, high rates of energy dissipation are required to break up droplets or bubbles. Recent interest has focused on the distribution of energy dissipation within the tank because the energy input through the shaft is not dissipated uniformly throughout the tank. For example, the radial disc turbine has a high power input and also has high rates of

energy dissipation in the vicinity of the impeller and low dissipation rates in the bulk flow.

2.4 Turbulence

Mixing in low viscosity system is determined by the amount of turbulence and rate of circulation generated by the impeller. The intensity of turbulence within the flow depends on the power input of the impeller. The circulation rate depends on the pumping capacity of the impeller. Many authors have calculated impeller discharge flow rates, Q, from velocity measurements in the vicinity of the blades (Nagata, 1975). Results are presented in dimensionless form as a discharge coefficient, N_Q, versus the impeller Reynolds number. The equation is

$$N_Q = Q/ND^3 = f(RE) \quad (5)$$

For low viscosity fluids, the flow usually turbulent ($Re > 10^4$) and the discharge coefficient is a constant, independent of impeller speed and diameter, so that the discharge flow rate is directly proportional to ND^3. Standard geometry disc turbine, (Uhl and Gray, 1966)

$$N_Q = Q/ND^3 = 0.75 \text{ for } 0.2 < D/T < 0.5 \quad (6)$$

also present a large number of discharge coefficients, N_Q, for various impellers in baffled and unbaffled vessels (Revill, 1982). The concept of the discharge flow gives a good qualitative indication of the impellers ability to generate fluid motion, but is not particularly useful in the design of mixing system, unless it can be directly linked to blend times or solids suspension criteria (Joshi *et al.*, 1982). Moreover, since the discharge stream leaving the impeller entrains other fluid from the bulk flow, Q is not the same as the circulation flow in the vessel.

The equation to calculate Reynolds number is

$$N_{Re} = (\rho N D_i^2)/\mu \quad (7)$$

where,

N_{Re} = Reynolds number

ρ = Density of liquid (kg/m^3)

N = impeller speed (rps)

D_i = impeller diameter (m)

μ = viscosity of liquid (Pa.s)

2.5 Power Consumption in Stirred Tank

2.5.1 Single Newtonian Liquid Phase

Calculation of the power input by agitation is of fundamental importance to both the process and mechanical design of stirred tanks. The fluid dynamics of stirred tanks is so complex as to preclude an a priori calculation of power input for a given impeller speed. In such cases, dimensional analysis can be used to indicate the form of the relationship between power and impeller rotational speed.

The ungassed power input, P_0, through a rotating impeller is a function of impeller speed, N, impeller diameter, D, liquid density, ρ_L, and liquid viscosity, μ_L, gravitational acceleration, g, and the tank geometry. The impeller speed is measured in revolution per second (rps) rather than radian per second. By making dimensionless analysis, the derived formula for the ungassed power number is given by

$$N_{P0} = P_0/\rho_L N^3 D^5 \quad (8)$$

where

N_{P0} = ungassed power number

P_0 = ungassed power consumption (W)

ρ_L = liquid density (kg/m^3)

N^3 = impeller speed (rps)

D^5 = impeller diameter (m)

A complete power characteristic for various impeller types is presented in figure 2.6. At low Reynolds number, the power number decrease as the Reynolds number increase while in the region where turbulent flow occurs, the power number become constant although the Reynolds number is increased. The baffled system indicates higher intensity of turbulence than unbaffled system hence improves the mixing rates.

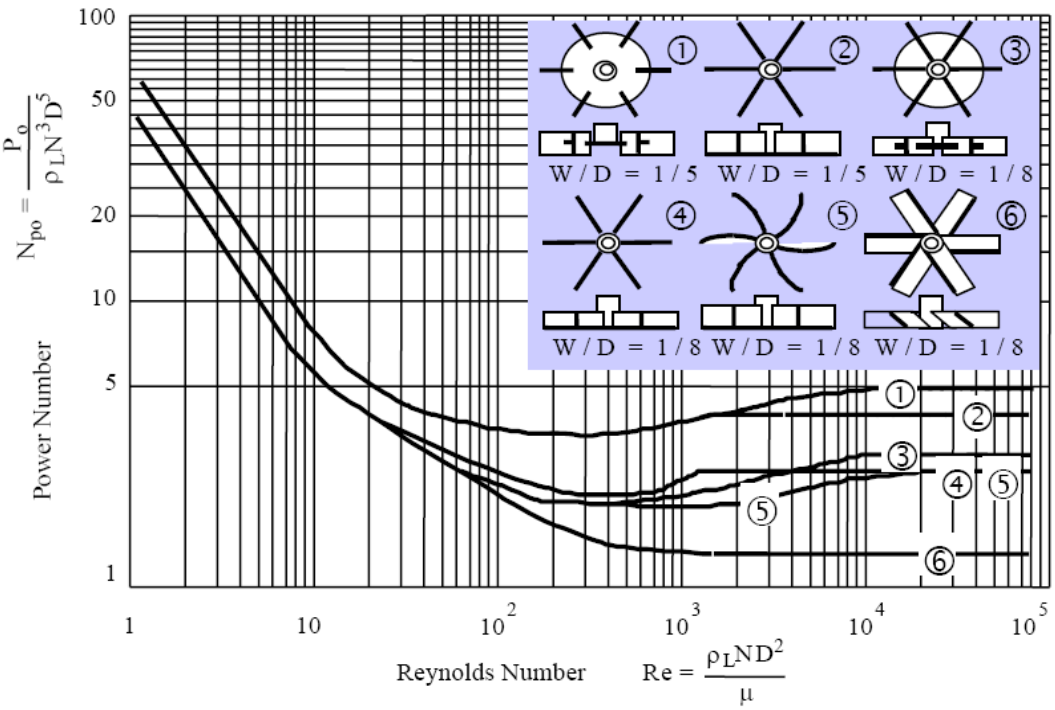


Figure 2.6 : Power characteristics for various impeller types in baffled tank

2.5.2 Reduced Power Consumption in Aerated Tank

The effect of sparging gas bubbles into a stirred tank is to substantially reduce the power consumption of the impeller. Ingas-liquid applications, the gassed power input is fairly high (~ 1-2 kW/m^3) since large energy dissipation rates produce small bubbles and large interfacial areas. (Uhl and Gray, 1966), (Nagata, 1975) and

(Greaves and Barigou, 1986) have reviewed the literature on power consumption under aerated conditions. The best known correlation is by Michel and Miller, 1962:

$$P_g = C(P_0^2 N D_i^3 / Q_g^{0.56})^{0.45} \quad (9)$$

where,

P_g = gassed power consumption (W)

C = constant (between 0.63 and 1.19 depending on tank geometry)

P_0 = ungassed power consumption (W)

N = impeller speed (rps)

D_i = impeller diameter (m)

Q_g = gas flow rate (m^3/s)

More recently workers have expressed their results in dimensionless terms by plotting the gassed power ratio (P_g/P_0) against the aeration number $N_Q=Q/ND^3$, at a constant impeller speed, as shown in the figure 2.7. This figure is for a standard geometry disc turbine, but data is available in the literature for many other impeller designs. Since the power input partly determines rates of mass transfer in gas-liquid dispersions it is important that the gassed power number does not drop off too rapidly, as aeration number increases. The Rushton turbine was formerly regarded as an efficient gas disperser. However it has a large ungassed power number and the power decreases by as much as 60% on aeration.

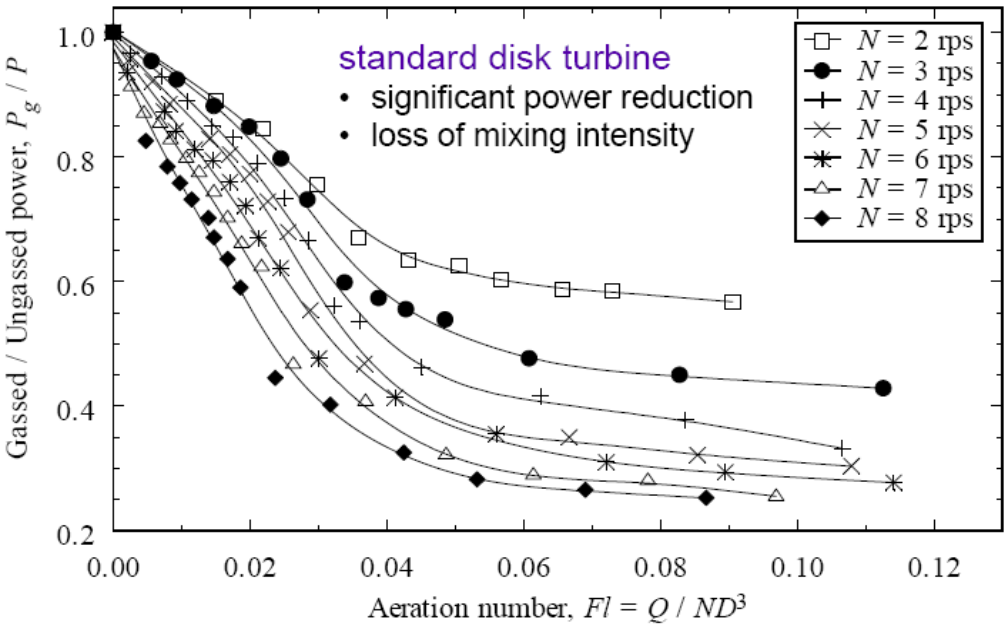


Figure 2.7 : Gassed power ratio for standard disc turbine

The decrease in power consumption is a consequence of the formation of stable gas cavities behind the impeller blades (Van't Riet and Smith, 1974). Gas sparged into the vessel is trapped in the vortices trailing behind each impeller blade and may remain there for several revolutions before being dispersed as small bubbles in the highly turbulent wake of each cavity. For a continuous flow of gas, at a sufficiently high impeller speed, stable gas cavities form behind each blade. The size and shape of these gas cavities depends on gas volumetric flow rate and impeller speed as illustrated in figure 2.8 below.

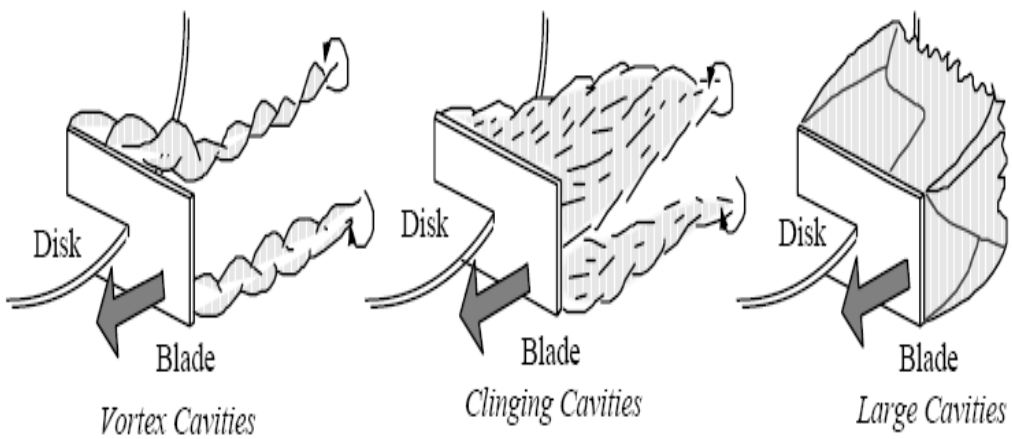


Figure 2.8 : Cavity shapes formed on blades during gas-liquid dispersion

At low gas flow rates, the bubbles are trapped in the trailing vortex system behind each blade and form so-called vortex cavities. As the sparged gas flow rate is increased the attached cavity size increases forming clinging and then large cavities. (Smith, 1986) has published flow regime maps (figure2.9) showing these cavity types as a function of the Froude and aeration numbers. For N_Q >~0.06, the cavities form themselves into a three-three configuration for six-bladed impellers which means there is a large and small cavities on alternate blades. The presence of these cavities alters the liquid streamlines around the blade, such that the separation point occurs further downstream from the leading edge of the blade. Formed drag on the impeller is decreased since the wake volume behind each blade is reduced by the presence of the gas cavity. Consequently, there is a reduction in power consumption in the presence of gas, which depends on the size and shape of the gas cavities.

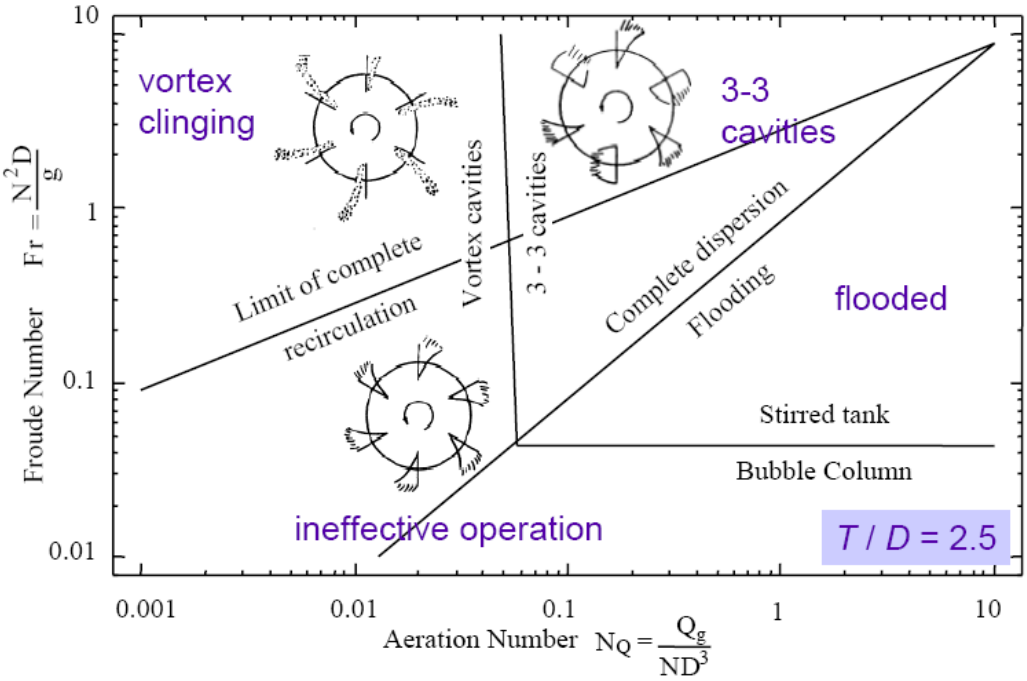


Figure 2.9 : Gas flow map for standard disc turbine (Smith, 1986)

2.6 Gas Flow Patterns

Figure 2.10 demonstrates the effects of gradually increasing the gas throughput or decreasing the impeller speed on gas flow patterns in a gas-liquid stirred tank (Nienow *et al.*, 1978).

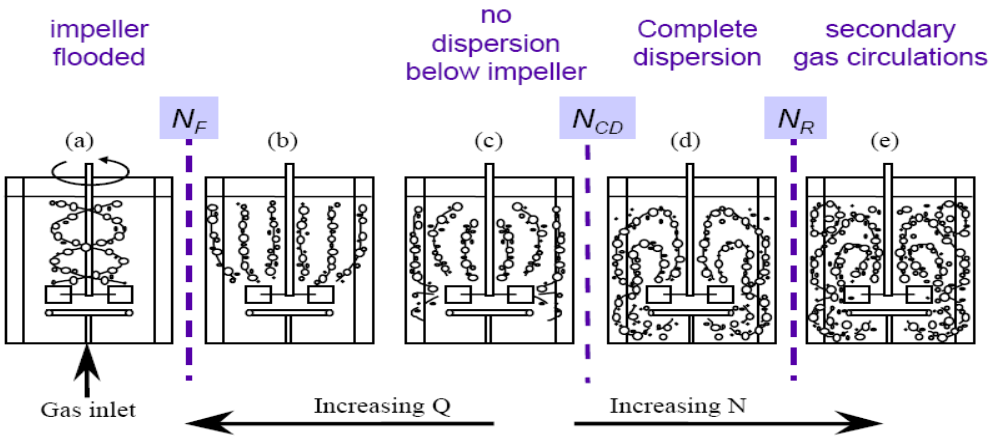


Figure 2.10 : Gas flow patterns as a function of impeller speed and gas flow rate (Nienow *et al.*, 1978)

At low gas flow rates and high impeller speeds, the bubbles are well dispersed above and below the impeller. With increasing gas flow, the gas dispersion becomes worse. (Nienow *et al.*, 1978) defined a critical speed for complete dispersion, N_{CD}, at the change from conditions (c) to (d). For H=T, C=T/4, 6-bladed disc turbines (valid for T<1.8m), Nienow *et al.* correlated their result by

Pipe spargers : $N_{CD} = 4Q^{0.5}T^{0.25}/D^2$ (10)

Ring spargers : $N_{CD} = 3Q^{0.5}T^{0.25}/D^2$ (11)

where,

N_{CD} = impeller speed for complete dispersion (rps)

Q = gas flow rate (m^3/s)

T = tank diameter (m)

D = impeller diameter (m)

These equations predict conservative values for non-coalescing systems and turbines with more than six blades (Middleton, 1985).

At constant impeller speed, the gassed power ratio becomes fairly constant at large values of aeration number, N_Q. Under this condition the cavities have grown to

their maximum size. Further increasing the gas throughput leads to “flooding”, corresponding to (a) in figure. In the flooded condition, not all of the gas passes through the gas cavities and some is not dispersed by the impeller. At this point, the impeller virtually stops pumping in the radial direction and a bulk liquid circulation is set up by the rising bubbles (Warmoeskerken and Smith, 1984). These workers showed theoretically that at the flooding point,

$$Q/N_F D^3 = 1.2 N_F^2 D/g \qquad (11)$$

where N_F is the critical impeller speed for flooding at a given gas volumetric flow rate, Q. Clearly, flooding is an undesirable condition which should be avoided in the practice since liquid phase mixing, gas dispersion and gas-liquid mass transfer are all adversely affected.

In many gas-liquid operations, the process objective is to maintain the same level of power input at different gas inputs to have a gassed power curve which is relatively flat without much reduction in the ratio of P_g/P_0. This ensures that bubble sizes and mass transfer coefficients are not impaired. Recent developments in impeller design have shown that large number of blades (12 or 18) or concave blades give this type of behavior (Middleton, 1985).

2.7 Operation Variables Affecting k_La Value

2.7.1 Impeller speed

The most important parameter affecting the design and the operation of the unit is the mass transfer coefficient, k_La. Many factors are known to affect aeration efficiency (k_La), including such parameters as agitation, air flow rate, air pressure, temperature, vessel geometry, fluid characteristics such as density, viscosity, surface tension, presence of antifoam agents, the concentration and physical properties of the immobilizing materials like density and particle size (Ozbek *et al*., 2000).

The values of k_La for distilled water versus impeller speeds are plotted in figure 2.11. The oxygen transfer coefficient, k_La, increased from 0.132 to 5.274 min^{-1} when the impeller speed was increased from 100 to 500 rpm. It can be also seen from figure 2.11 that the impeller speed versus k_La plot could be considered in two regions. In the first region, below 300 rpm, the slope is much lower. In the second region, above 300 rpm, k_La increases linearly with an increase in the speed of the impeller.

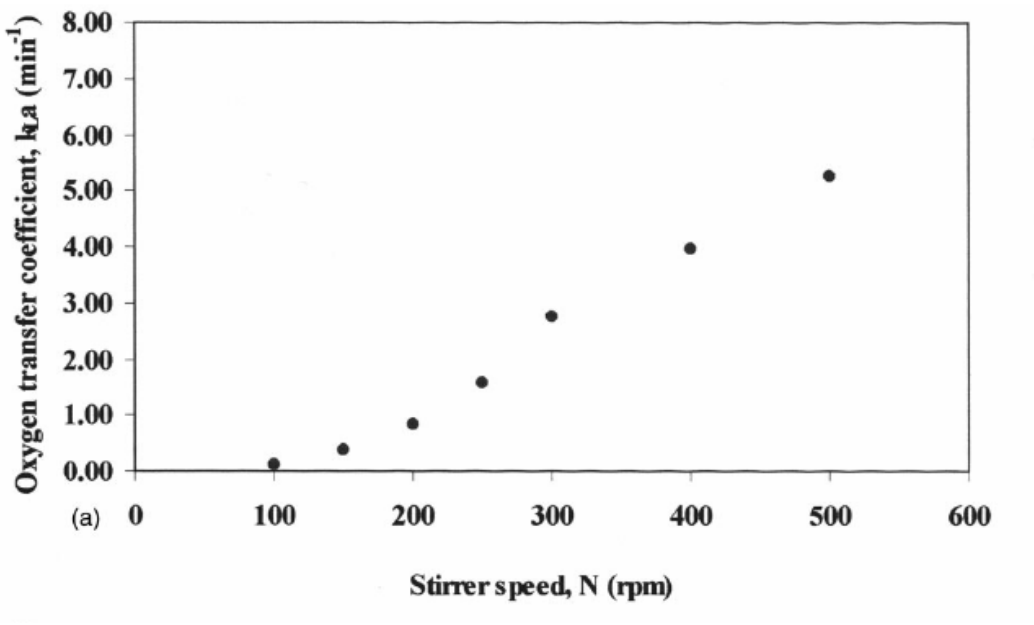


Figure 2.11 : Effect of stirrer speed on k_La in distilled water

(Westerterp *et al*., 1963) observed similar results in their studies. He suggested that there is a critical impeller speed, N_C, above which a linear function of impeller speed only occurs. He found that different critical speeds ranged from 200 to 650 rpm depending on the geometry used.

The exponential relationship between the k_La and the power number (N^3D^2) is given in Eq. (12). The values of k_La for distilled water versus power number on the log–log basis are plotted in Figure 2.12. The statistical values of R^2 and standard error (σ) obtained by using the data were 0.9999 and 0.00016, respectively.

$$k_La \ \alpha \ (N^3D^2)^{0.42}. \qquad (12)$$

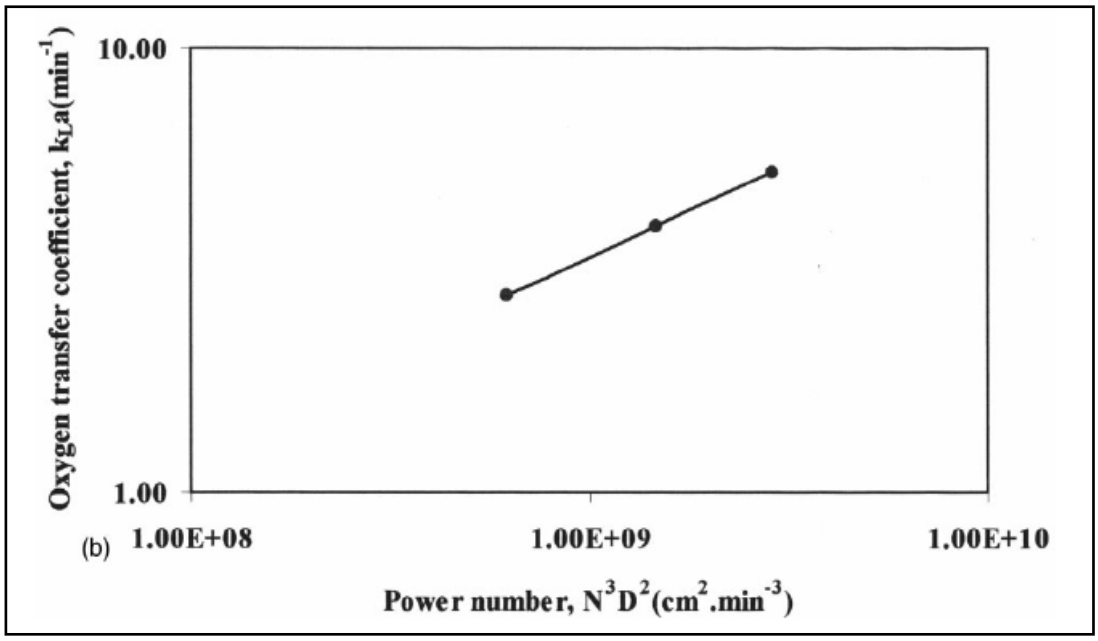


Figure 2.12 : k_La values versus power numbers in distilled water

For gas sparged agitated vessels, the literature indicates a large variation in the exponent of P/V_L (0.4–1.0) for geometrically different vessels. Here, P is power consumption and V_L is liquid volume. In the absence of power measurement equipment, the exponents of N^3D^2 were obtained for the power number. The exponents of P/V_L and N^3D^2 are similar and the relationship that can be written between them as $P/V_L=C\ N^3D^2$. The constant, C, could be different for different gas loadings in the vessel, therefore, the exponent of P/V_L may be different than the exponent of N^3D^2. The exponent of N^3D^2 obtained from the study by (Ozbek, 2000) where α=0.42, is in the range obtained from the previous literature (0.16–0.68). This is because of the fact that, the geometry of the vessel such as the proportionality of impeller diameter to vessel diameter, tank bottom geometry and tank liquid height is different from the others.

2.7.2 Air flow rate

In the study by (Ozbek, 2000) where experiments were performed at aeration rates of 0.3 and 0.6 l min^{-1} at a working volume of 0.6 l, impeller speed 300 rpm, temperature of 37°C and pH of 7.0, for distilled water, the effects of aeration rates on the k_La were investigated using the aeration rates in the range of 0.15–0.9 l min^{-1}. The oxygen transfer coefficient, k_La, increased from 1.728 min^{-1} to 5.35 min^{-1} when the aeration rate was increased from 0.15 to 0.9 l min^{-1}, respectively. The values of k_La for distilled water are plotted in figure 2.13.

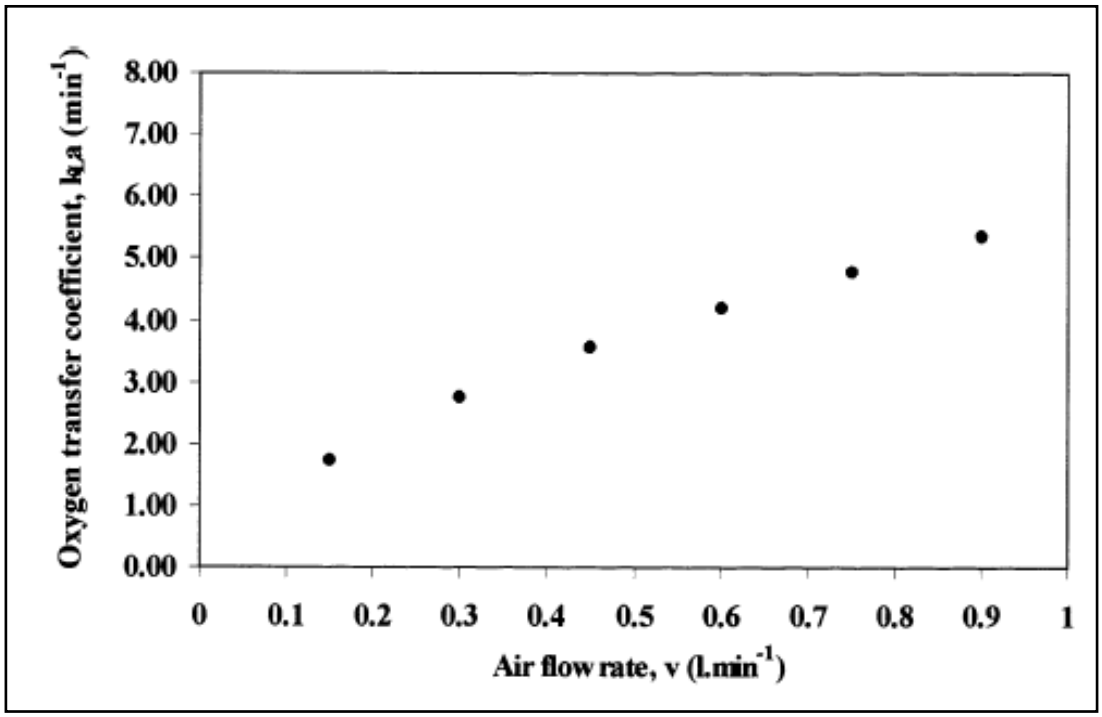


Figure 2.13 : Effects of air flow rate on k_La values in distilled water

The exponential relationship between the k_La and the superficial gas velocity (Vs) for the study by (Ozbek, 2000) is given in Eq. (13). The statistical values of R^2 and standard error (σ) obtained using the data were 0.9995 and 0.00075, respectively.

$$k_La \ \alpha \ (Vs)^{0.62} \qquad (13)$$

The exponent (β=0.62) representing the dependence of k_La on the superficial gas velocity (Vs) was compared with the previous literature. Previous investigators obtained the values of the exponent on the superficial gas velocity ranged from 0.17 to 0.67, depending on the agitator speed and the geometry of the equipment.

2.8 Methods to Determine Volumetric Mass Transfer (k_La) of Oxygen

2.8.1 Static Gassing Out and Other Methods

Current bibliography provides several methods to determine the k_La values in bio-reactors. The most widely used are the methods of static gassing-out, dynamic gassing-out, oxygen balance and sulphide oxidation. The poorest results are obtained by means of the sulphide oxidation method. This one has proved to be unuseful for fermentations at the same time that numeric results get higher values than those obtained by the other methods. The oxygen balance method requires high precision for the measurement of gas inlet- and outlet rates, and for the determination of the dissolved oxygen concentration in the liquid phase.

The static and dynamic gassing-out method is based on the recording of the saturation curve of oxygen after the oxygen inlet flow has been interrupted. Comparing both methods, the static gassing-out is the simplest one and provides results which are easier to interpret (I. de Ory, L.E. Romero, D. Cantero, 1999). The techniques for k_La measurements vary widely (D.I.C. Wang *et al.*, 1979) which is due to uncertainties coupled with each particular method-They arise mainly from the complications encountered with the physico-chemical properties of culture liquids. It is now more and more accepted that purely chemical methods as for example the sodium sulfite oxidation (Cooper *et al.*, 1944) yield values for k_La of very limited relevance.

2.8.2 Sum Squared Error Minimization Analysis

The value of k_La and ka_p can be determined by minimization of a function. The function to be minimized is

$$F(t) = SUM\ [YS(t) - YR(t)]^2 \quad (14)$$

where,

F(t) = function to be minimized

SUM = summation of squared error between YS(t) and YR(t)

YS(t) = dissolved oxygen concentration from experiment at time t

YR(t) = theoretical dissolved oxygen concentration at time t

The value of YR(t) is functioning to k_La and ka_p while the value of k_La and ka_p is determined by using the sum squared error minimization of a function. Since the value of YS(t) is changing with time t, it is necessary to determine the value of YR(t) at each of the time t. The value of k_La and ka_p obtained from the function error minimization using MATLAB can be utilized to recalculate the value of YR(t) by using equation (4) to be analyzed. The MATLAB programming will iterate the value of k_La and ka_p for several times until the k_La and ka_p converged to a value that will minimized the function, F(t).

CHAPTER 3

METHODOLOGY

3.1 Design

The standard design of a stirred tank was studied in order to design the bioreactor experimental rig. After that, the rig was designed according to the standard geometry including the dimension of the vessel, impellers, air sparger, baffles and the support of the rig. The rig was designed appropriately in order to provide good gas-liquid mixing within the system. The diameter of the tank to be constructed was determined before calculating the other dimension of the rig. The design of the tank and impeller can be illustrated by the following figures and tables.

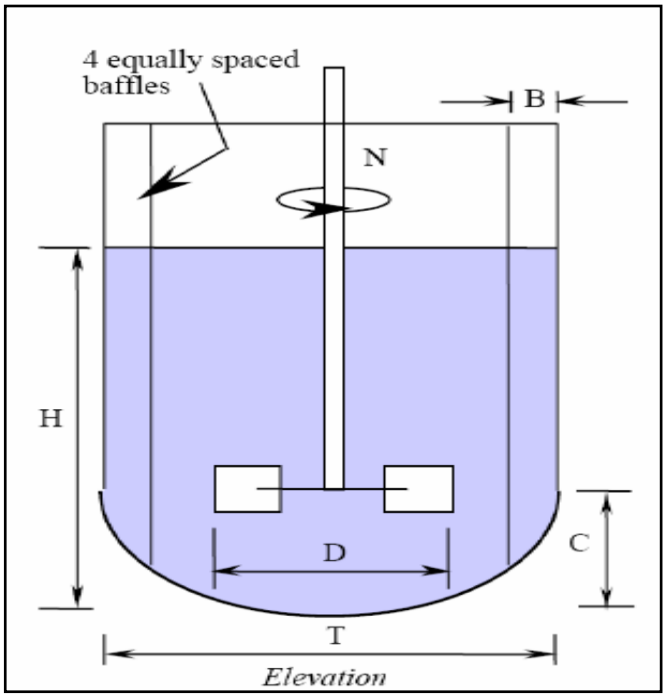


Figure 3.1 : Standard geometry of a stirred tank

Table 3.1 : Standard geometrical ratio of a stirred tank

Geometric Ratio	Standard Geometry
H/T	1
D/T	1/3
C/T	1/3
C/D	1
B/T	1/10

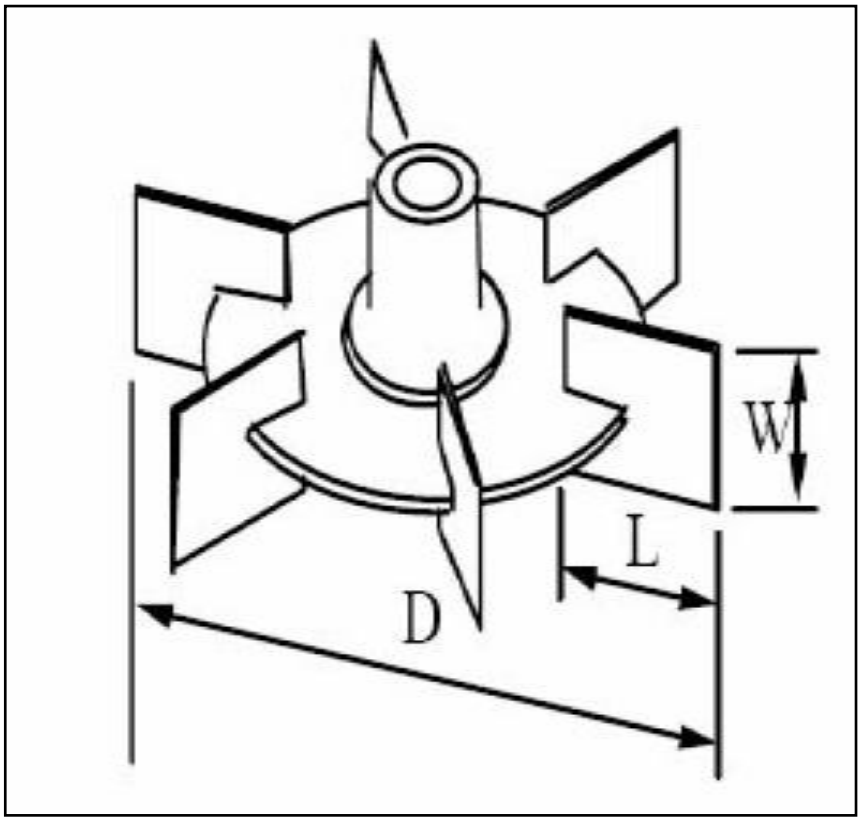


Figure 3.2 : Standard geometry of a Rushton disc turbine impeller

Table 3.2 : Standard geometrical ratio of a Rushton disc turbine impeller

Geometric Ratio	Standard Geometry
L/D	1/4
W/D	1/5
Disc diameter/D	3/4

The designed geometry of the rig was sketched for construction.. Appropriate base for the bioreactor experimental rig was designed for the ease of draining the liquid content inside the tank after experiment is conducted.

3.2 Construction

The bioreactor experimental rig was constructed based on the designed geometry. The construction process was done with the help of Assistant Training Vocational at the engineering workshop. Transparent Polyvinylchloride was used as a construction material for the tank while 2 set of impellers, ring air sparger and 4 pieces of baffles were constructed using stainless steel in order to avoid corrosion.

3.3 Experimental Method

Static Gassing Out method was used in order to produce the DOT curves for each operation variables to be studied. In this work, the operation variables studied are impeller speed and air flow rate. In order to study the effect of impeller speed towards k_La and ka_p, the speed was varied between 200 rpm until 400 rpm. For each impeller speed commissioned, the data of dissolved oxygen tension (DOT) was taken within the time interval of 1 minute until the DOT reading was constant.. For the second experiment, in order to study the effect of air flow rate towards k_La and ka_p value, the air flow rate was varied between 1 L/min to 3L/min. For each air flow rate commissioned, the data of DOT was also taken within the time interval of 1 minute until the reading was constant. The detailed methodology to study the effect of both operation variables were described in the next subsection.

3.3.1 Effect of Impeller Speed on k_La and ka_p

1) The rig was set up by connecting it with DO probe, air pump and air flow meter.
2) The tank was filled with 3.5 L volume of distilled water.
3) Calibration of the DO probe was done following the standard operating procedure.
4) The impeller speed was set at 200 rpm.
5) Without connecting the air flow cable to the rig, the air pump was switched on and the air flow rate was set at 1 L/min.
6) The N_2 gas cable was connected to the air sparger port.
7) Distilled water in the tank was sparged with nitrogen (N_2) gas until DO reading achieve zero.
8) The N2 cable was disconnected from the air sparger port and replaced by air flow cable. The air pump was switched on.
9) The DO reading at t=0 was taken and it was continuously taken at a time interval of 1 minute until DO reading was constant.
10) Steps 5 to 7 were repeated by manipulating the impeller speed in step 4 at 250,300,350 and 400 rpm.
11) The DOT reading for each impeller speed commissioned was analyzed using the sum squared error minimization method in the MATLAB programming to get the value of k_La and ka_p for each impeller speed.

3.3.2 Effect of Air Flow Rate on k_La and ka_p

1) The rig was set up by connecting it with DO probe, air pump and air flow meter.
2) The tank was filled with 3.5 L volume of distilled water.
3) Calibration of the DO probe was done following the standard operating procedure.
4) The impeller speed was set at 250 rpm.
5) Without connecting the air flow cable to the rig, the air pump was switched on and the air flow rate was set at 1 L/min.

6) The N_2 gas cable was connected to the air sparger port.
7) Distilled water in the tank was sparged with nitrogen (N_2) gas until DO reading achieve zero.
8) The N_2 gas cable was disconnected from the air sparger port and replaced by air flow cable. The air pump was switched on.
9) The DO reading at t=0 was taken and it was continuously taken at a time interval of 1 minute until DO reading was constant.
10) Steps 5 to 7 were repeated by manipulating the air flow rate in step 5 at 1.5, 2.0, 2.5, and 3 L/min.
11) The DOT reading for each air flow rate commissioned was analyzed using the sum squared error minimization method in the MATLAB programming to get the value of k_La and ka_p for each air flow rate.

3.4 Analysis of k_La and ka_p Value using Sum Squared Error Minimization in MATLAB Programming.

1) MATLAB 6.5 program was open.
2) M-File was created to hold the function for sum squared error minimization between theoretical data and actual data. The function is

   F(t) = SUM [YS(t) – YR(t)]^2

   % f = SUM (YS(t) – (C*-C*((ka$_p$.exp(-k$_L$a.t))/(ka$_p$-k$_L$a) – (k$_L$a.exp(-ka$_p$.t))/(k$_L$a-ka$_p$))))^2

   % By replacing kap with x(1) and kLa with x(2) :

   f = k(x)

   % f = SUM(YS(t) – (8.13-8.13((x(1)*.exp(-x(2)*.t))/(x(1)-x(2)) – (x(2)*exp(-x(1)*t))/(x(2)-x(1)))))^2

   f = (YS(1)-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-x(1)))))^2+(YS(2)-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*2)/(x(2)-x(1)))))^2+(YS(3)-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+……
3) Command window was opened.

4) Command for function value minimization was coded in the command window. The function is

```
fminsearch('k',[x1,x2])
% x1 = initial guess for the value of x(1)
% x2 = initial guess for the value of x(2)
```

3.5 Do's and Don'ts during Commissioning Process

3.5.1 Do's

1) Assemble the retort stand that holds the motor above the tank from the side of the rig.
2) Make sure the impeller just above the air sparger before starting the experiment.
3) Make sure that the top plate is tightened up before commencing the experiment in order to avoid spillage of liquid that can damage the motor.
4) Close the valve at the drainage system below the tank before filling in the liquid into the tank.
5) Make sure the impeller speed and air flow rate did not largely fluctuate from the set value.
6) Calibrate the DO meter before the experiment is started.
7) Make sure the cables are appropriately connected to the rig.

3.5.2 Don'ts

1) Do not let the motor touching the DO probe during the experiment is conducted. The vibration of the motor can reduce the accuracy of the DO readings.
2) Do not leave the liquid content remains in the tank after doing the experiments. Drain the liquid after finish using the rig.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this study, the work is done beginning from the design of the bioreactor experimental rig. After that, the rig was constructed based on the design work and finally the rig was commissioned in order to study the effect of two operation variables towards the value of k_La and ka_p which are impeller speed and air flow rate.

The design works is the crucial part of this study in order to create a system that can provide a good mixing in the liquid-gas system. The construction of the rig was properly done with the help from well experienced Assistant Training Vocational to build a robust system for experimental study. Finally, the rig was used to run the experiment in order to study the effect of impeller speed and air flow rate towards k_La and ka_p by applying the static gassing out method.

So, the result of this study can be divided into three sections which are the design, construction and commissioning.

4.2 Design

By doing literature study, a rig with standard geometry to provide good gas-liquid mixing was produced. The rig has typical dimension as illustrated by the figure and table below.

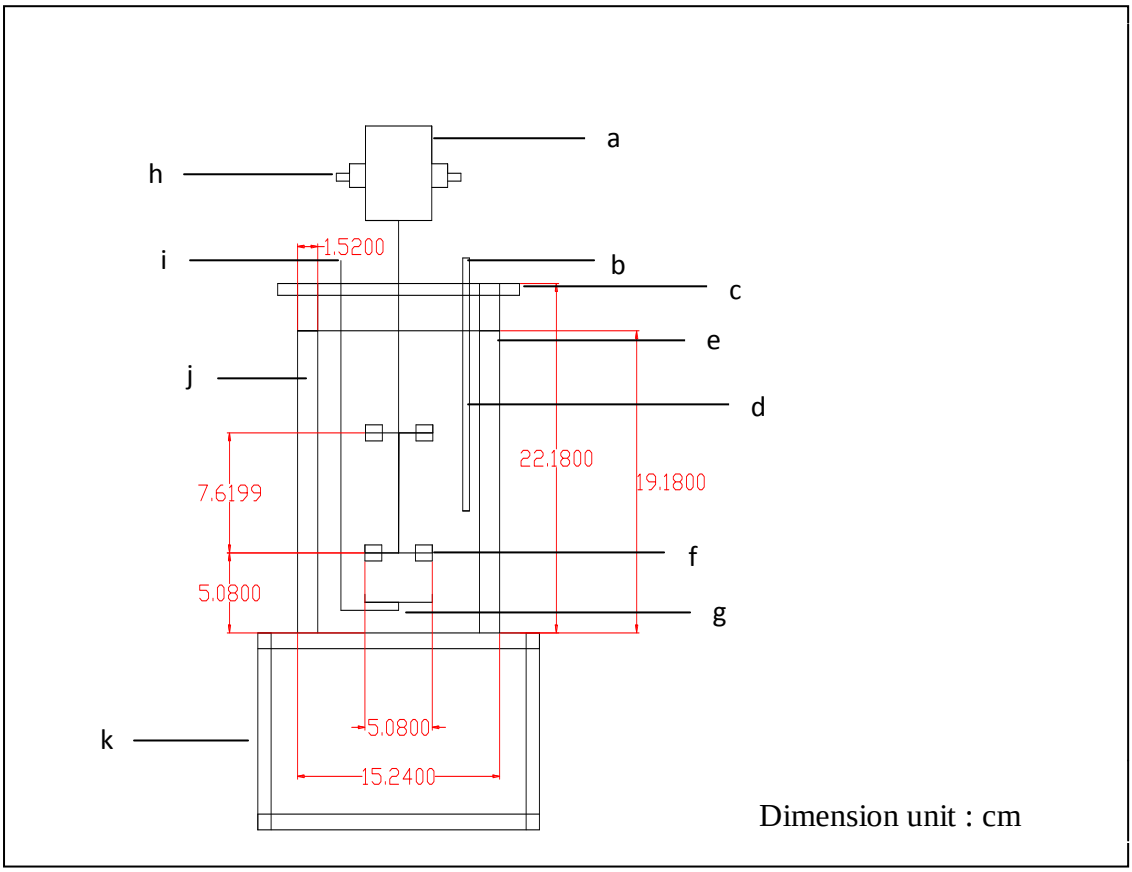


Figure 4.1 : Bioreactor experimental rig design

Table 4.1 : Specification of the designed rig

Label	Name
a	Motor
b	DO probe's port
c	Top plate
d	DO probe
e	Tank
f	Impeller
g	Ring air sparger

h	Retort stand
i	Air sparger's port
j	Baffle
k	Base support

Table 4.2 : Geometry and dimension of the designed rig

Geometry	Dimension (cm)
Tank height, H_t	22.18
Liquid height, H_L	19.18
Tank diameter, D_t	15.24
Impeller diameter, D_i	5.08
Distance between impeller, H_i	7.62
Baffle width, B	1.52
Bottom clearance, C	5.08

Table 4.3 : Geometry and dimension of Rushton disc turbine impeller

Geometry	Dimension (cm)
Impeller diameter, D_i	5.08
Disc diameter	3.81
Blade length, L	1.27
Blade width, W	1.02

The rig was designed based on the standard geometry of a stirred tank. The impeller selected for this system is Rushton disc turbine impeller because it can give the best result for gas dispersion in gas-liquid system. A good mixing of the sparged air with the distilled water inside the tank is important in order to reduce the barrier for oxygen transport process as much as possible. The RDT impeller produced radial discharge flow of liquid inside the tank. Baffling redirects the radial flow in the impeller discharge stream, generating strong vertical circulations. The support base was designed to hold the tank stably while doing the commissioning process. Besides, with this type of base support, the liquid content inside the tank can be easily drained after each experiment.

4.3 Construction

After the rig was completely designed, the construction phase begun with the help from the Assistant Training Vocational in the Engineering Workshop. The bioreactor experimental rig produced after the construction went to completion can be seen in the appendices.

The tank was built by using transparent PVC in order to produce a see-through bioreactor experimental rig. Besides, the transparent PVC can be easily joined by using the PVC weld. PVC welding can produce a robust system by providing sufficient support at the tank's joint in order to withstand the hydrostatic pressure exerted by the liquid height inside the tank. The tank's joints were welded with multiple layer of PVC welding to avoid leakage. Besides, the pores made on the air sparger were made facing downward in order to avoid the liquid from entering the pores.

In order to avoid corrosion, the impeller and baffles were built of stainless steel. Two impellers were constructed because the ratio of liquid height to tank diameter (H_L/D_t) was about 1.26. The standard design of a stirred tank suggest that, with H_L/D_t between 1 to 1.3, two sets of impeller needed to improves mixing and mass transfer throughout the tank (Najafpour, 2007). The distance between these two impellers, H_i were set at $1.5D_i$ since the condition to produce good mixing is $D_i < H_i < 2D_i$. A bearing was installed at the top plate to hold the agitator's shaft to avoid unstable spin of impeller during experiment. At the top plate, a rubberized material was used between the plates to seal the system in order to avoid liquid spillage during the experiment which can damage the motor.

4.4 Commissioning

4.4.1 Effect of ImpellerSpeed on k_La and ka_p

Table 4.4 : Result for the effect of impeller speed on k_La and ka_p

Impeller speed, N (rpm)	k_La (min^{-1})	ka_p (min^{-1})
200	1.5236	0.2193
250	1.5137	0.2585
300	3.2237	0.3393
350	4.077	0.4366
400	5.7405	0.5056

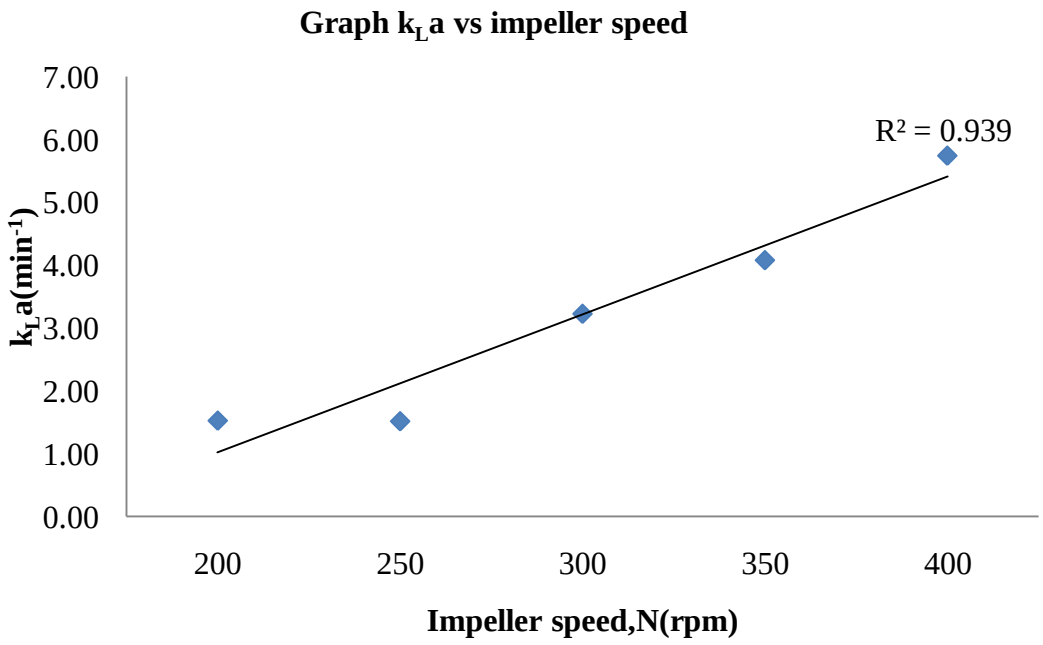


Figure 4.2 : Graph k_La versus impeller speed

From the graph shown above, it can be said that the k_La increased as the impeller speed was increased. The proportionality of increment of the k_La values with incresing impeller speed gave a coefficient of 0.939. This value was quiet close to the value of 1 where direct proportionality occurred. With higher impeller speed, the bubbles size will be reduced. This will result in the increase of interfacial area for mass transfer process per unit volume of bubbles Also, as the impeller speed increased, the turbulence of the flow regime is higher. This phenomenon reduced the amount of barriers encountered for mass transfer of oxygen from the air bubbles to the bulk liquid. Since the value of k_La is reciprocal to the total amount of mass

transfer resistance encountered in mass transfer process, the reduction of resistance due to higher turbulence created with increasing impeller speed had result in the increment of k_La.

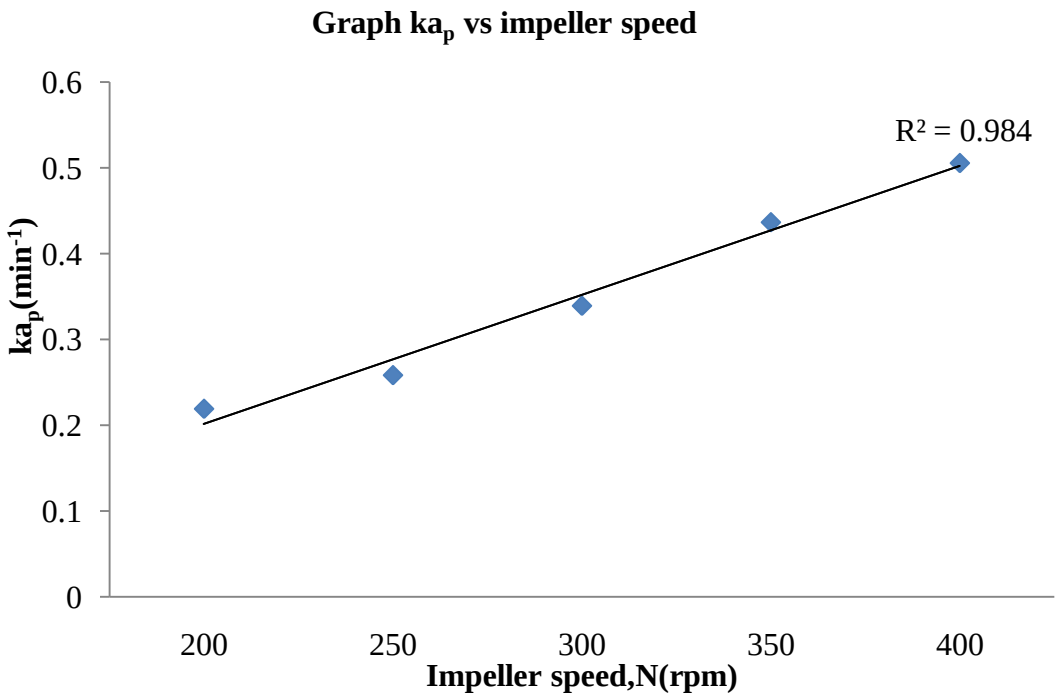


Figure 4.3 : Graph of ka_p versus impeller speed

From the graph shown above, it can be said that the ka_p increased as the impeller speed was increased. The proportionality of increment of the ka_p values with incresing impeller speed gave a coefficient of 0.984. This value was quiet close to the value of 1 where direct proportionality occurred. At higher impeller speed, the turbulence of the flow regime is higher. This phenomenon reduced the amount of barriers encountered for mass transfer of oxygen from the bulk liquid to the electrode of DO probe. With higher impeller speed, the bubbles size will be reduced. This will result in the increase of interfacial area for mass transfer process per unit volume of bubbles.At higher turbulence, the film resistance surrounding the electrode's membrane will be thinner. So, it is easier for the oxygen to be transfered to the membrane for detection. Since the value of ka_p is reciprocal to the total amount of mass transfer resistance encountered in mass transfer process, the reduction of resistance due to higher turbulence created with increasing impeller speed had result in the increment of ka_p.

4.4.2 Effect of Air Flow Rate on k_La and ka_p

Table 4.5 : Result for the effect of air flow rate on k_La and ka_p

Air flow rate, Q_g (L/min)	k_La (min^{-1})	ka_p (min^{-1})
1.0	1.5069	0.1645
1.5	1.5879	0.2007
2.0	1.7479	0.2400
2.5	1.7887	0.2712
3.0	1.9269	0.3183

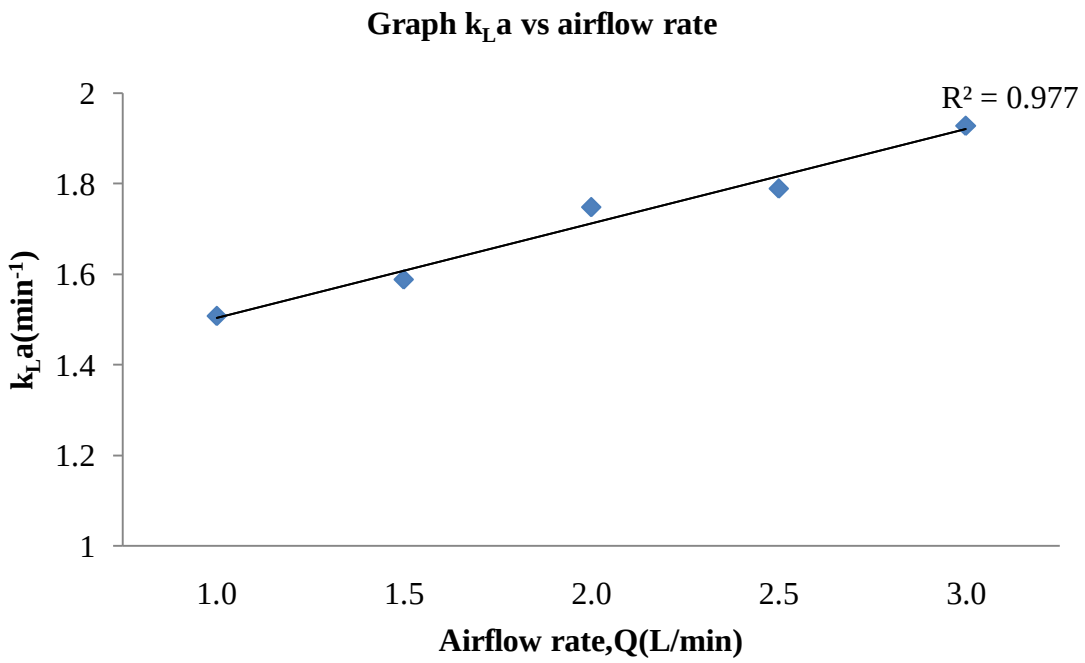


Figure 4.4 : Graph of k_La versus air flow rate

From the graph shown above, it can be said that the k_La increased as the air flow rate was increased. The proportionality of increment of the k_La values with increasing air flow rate gave a coefficient of 0.977. This value was quiet close to the value of 1 where direct proportionality occurred. At higher air flow rate, the gas hold up increased. Higher gas hold up provides larger interfacial area for mass transfer of oxygen from the air bubbles to the bulk liquid. Also, at higher air flow rate, the superficial gas velocity will increase. The increment of superficial gas velocity creates greater turbulence in the liquid flow regime. High turbulence caused the film resistance from the air bubbles to the liquid medium to be thinner. Since the value of k_La is reciprocal to the total amount of mass transfer resistance encountered in mass

transfer process, the reduction of resistance due to higher turbulence created with increasing air flow rate had result in the increment of k_La.

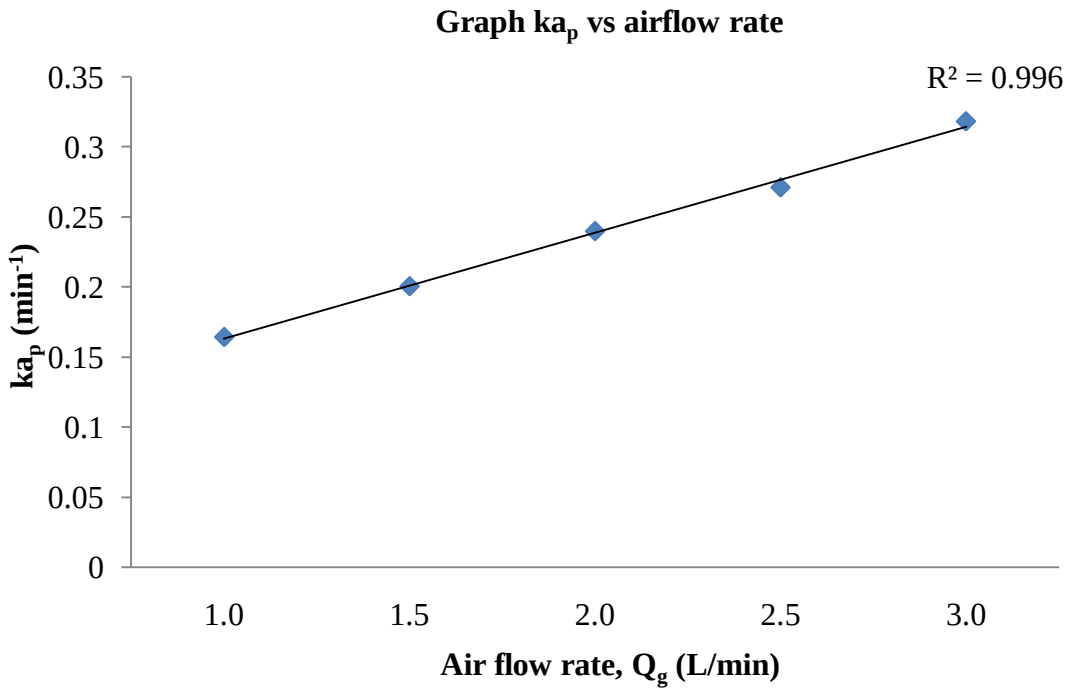


Figure 4.5: Graph of ka_p versus air flow rate

From the graph shown above, it can be said that the ka_p increased as the air flow rate was increased. The proportionality of increment of the ka_p values with increasing air flow rate gave a coefficient of 0.996. This value was quiet close to the value of 1 where direct proportionality occured. At higher air flow rate, the superficial gas velocity will increase. The increment of superficial gas velocity creates greater turbulence in the liquid flow regime. High turbulence caused the film resistance surrounding the electrode's membrane to be thinner. Thus, the total resistance for mass transfer of oxygen from the bulk liquid to the electrode's membrane reduced. Since the value of ka_p is reciprocal to the total amount of mass transfer resistance encountered in mass transfer process, the reduction of resistance due to higher turbulence created with increasing air flow rate had result in the increment of ka_p.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, the fabrication of this bioreactor experimental rig can serve more practical commissioning of experiment to study the effect of different operation variables on the k_La and ka_p value. The lab session that include the measurement of k_La and ka_p does not has to be postponed due to the problem arise when the session intercept with the research study done by the postgraduate student.

The existence of this bioreactor experimental rig can also avoid the damage of existing 10L fermenter due to the mishandling of experiment done by the students during the lab session. The rig can replace the 10L fermenter as a more appropriate equipment to measure the dissolved oxygen tension (DOT) in order to study about the k_La and ka_p. As the experiment in this work had successfully commissioned and produced sets of reliable data, it can be conclude that the design of this bioreactor experimental rig is capable of providing good mixing in gas-liquid system.

From the analysis of data in the experiment done in this work, it can be seen that the value of k_La and ka_p will increase if the impeller speed and air flow rate is increased. Thus, impeller speed and air flow rate are important operation variables that need to be considered before running a process that requires a good mixing condition for oxygen transport mechanism as both of the operation variables give significant effect to the k_La and ka_p value.

5.2 Recommendation

From my experience doing this study, there are several recommendations that can be made for the future study. The recommendations are stated below.

1) I hope that the faculty can provide financial support to buy a new motor, DO meter, air flow meter and an air pump to be permanently assembled to this bioreactor experimental rig so that the commissioning of this rig in the future will be simpler and the result will be more accurate.

2) For further study on k_La and ka_p, try to figure out the effect of other operation variables such as for different types or number of impellers and the presence of electrolyte. For advance, modify the rig in order to make it capable to study the effect of temperature on k_La and ka_p.

3) Modify the M-File and coding for sum squared error minimization using MATLAB programming into simpler form so that the way how the data is analysed will be easily understand.

4) Replace the air sparger with a new one that has smaller pore size in order to produce smaller bubbles for good mixing and mass transfer.

5) Use the MATLAB programming for fermentation scale up at constant k_La and ka_p

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APPENDIX A

Images of the Constructed Bioreactor Experimental Rig

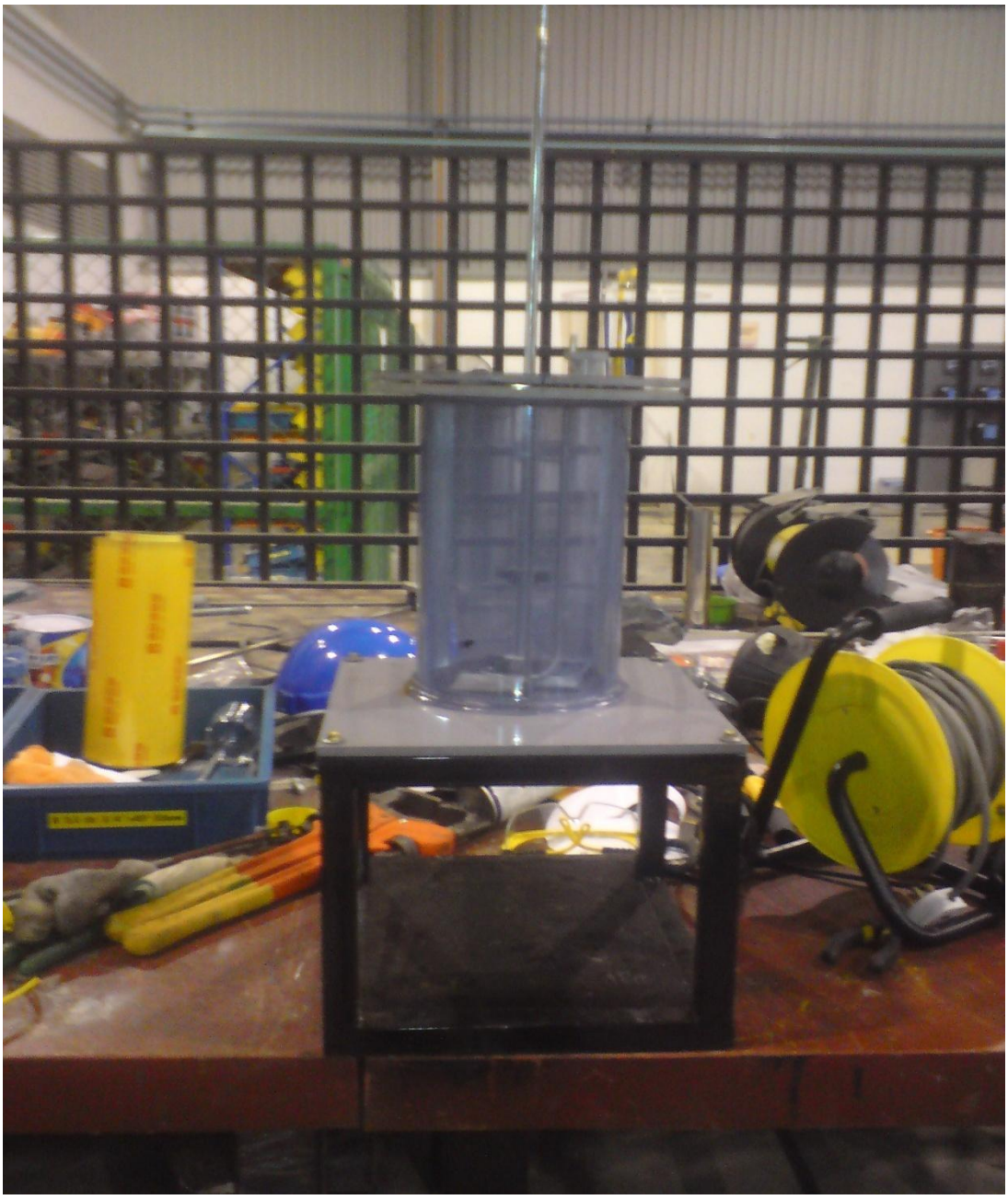

Figure A1 : Front view of the constructed bioreactor experimental rig

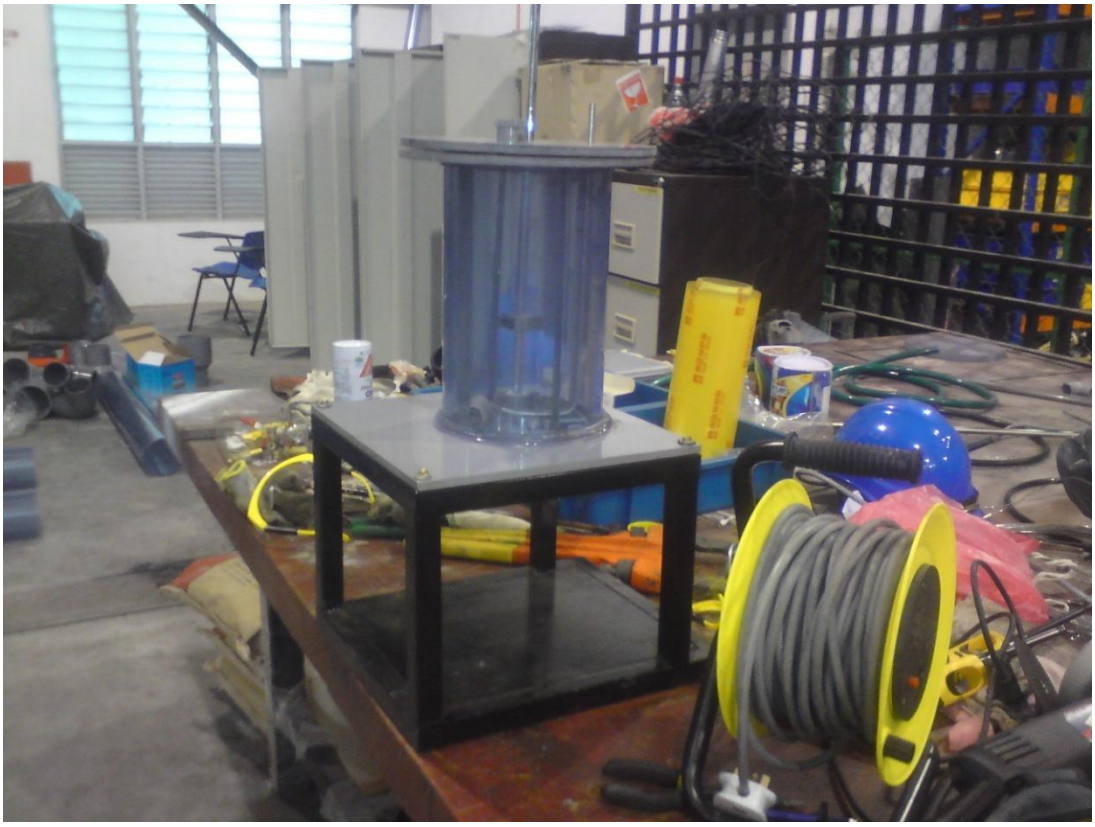

Figure A2 : Frontside view of the constructed bioreactor experimental rig

Figure A3 : Backside view of the constructed bioreactor experimental rig

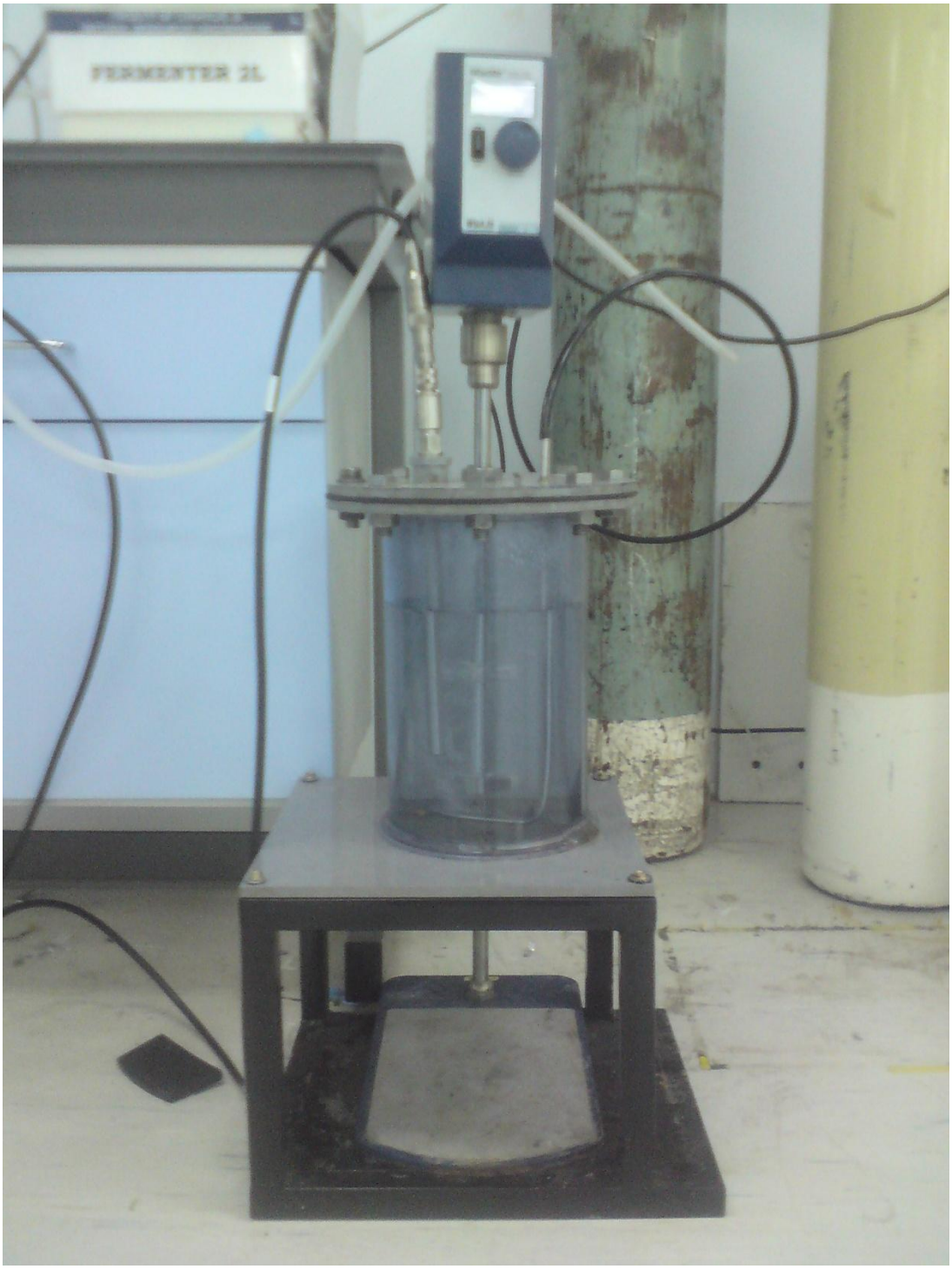

Figure A4 : Bioreactor experimental rig ready to be commissioned

APPENDIX B

DOT AND DOC VERSUS TIME DATA

Effect of impeller speed on k_La and ka_p

Air flow rate : 2 L/min

Impeller speed : 200 rpm

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	13.3	1.0813
2	27.6	2.2439
3	38.8	3.1544
4	49.4	4.0162
5	59.6	4.8455
6	67.8	5.5121
7	72.7	5.9105
8	77.3	6.2845
9	84	6.8292
10	87.9	7.1463
11	89.3	7.2601
12	92.4	7.5121
13	94.9	7.7154
14	98.2	7.9837
15	99.8	8.1137
16	100	8.1300
17	100	8.1300

Air flow rate : 2 L/min

Impeller speed : 250 rpm

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	12.5	1.0163
2	29.7	2.4146
3	45	3.6585
4	56.4	4.5853
5	65.6	5.3333
6	73.8	5.9999
7	79.3	6.4471
8	84.6	6.8780
9	87.9	7.1463
10	91.4	7.4308
11	93.6	7.6097
12	95.5	7.7642
13	96.9	7.8780
14	98.1	7.9755
15	99	8.0487
16	100	8.1300
17	100	8.1300

Air flow rate : 2 L/min

Impeller speed : 300 rpm

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	21.8	1.7723
2	42.6	3.4634
3	58.4	4.7479
4	72	5.8536
5	79.9	6.4959
6	85.2	6.9268
7	89.4	7.2682
8	92.9	7.5528
9	94.9	7.7154
10	96.5	7.8455
11	97.4	7.9186
12	98.6	8.0162
13	98.9	8.0406
14	99.3	8.0731
15	99.5	8.0894
16	100	8.1300
17	100	8.1300

Air flow rate : 2 L/min

Impeller speed : 350 rpm

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	28.2	2.2927
2	52.7	4.2845
3	69.9	5.6829
4	79.8	6.4877
5	88.2	7.1707
6	91.2	7.4146
7	95.2	7.7398
8	96.9	7.8780
9	98.2	7.9837
10	98.8	8.0324
11	99.3	8.0731
12	99.7	8.1056
13	100	8.1300
14	100	8.1300

Air flow rate : 2 L/min

Impeller speed : 400 rpm

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	35	2.8455
2	57.9	4.7073
3	75.8	6.1625
4	85.9	6.9837
5	92.1	7.4877
6	95.3	7.7479
7	97.4	7.9186
8	98.7	8.0243
9	99.3	8.0731
10	99.9	8.1219
11	100	8.1300
12	100	8.1300

Effect of Air flow Rate on k_La and ka_p

Impeller speed : 250 rpm

Air flow rate : 1 L/min

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	9.4	0.7642
2	19.1	1.5528
3	31.3	2.5447
4	41.6	3.3821
5	51.5	4.1870
6	59.6	4.8455
7	63.9	5.1951
8	69.1	5.6178
9	73.1	5.9430
10	77	6.2601
11	80.6	6.5528
12	84.7	6.8861
13	87	7.0731
14	89.3	7.2601
15	90.8	7.3820
16	92	7.4796
17	93.6	7.6097
18	94.8	7.7072
19	95.5	7.7642
20	96.2	7.8211
21	96.9	7.8780
22	97.3	7.9105
23	98	7.9674
24	98.5	8.0081
25	98.9	8.0406
26	99.5	8.0894

27	99.8	8.1137
28	100	8.1300
29	100	8.1300

Impeller speed : 250 rpm

Airflow rate : 1.5 L/min

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	11.2	0.9106
2	23.5	1.9106
3	37.2	3.0244
4	48.4	3.9349
5	58.7	4.7723
6	64.9	5.2764
7	71.3	5.7967
8	76.9	6.2520
9	81.1	6.5934
10	84.4	6.8617
11	87	7.0731
12	89.4	7.2682
13	91.9	7.4715
14	93.2	7.5772
15	94.7	7.6991
16	95.9	7.7967
17	96.7	7.8617
18	97.8	7.9511
19	98.1	7.9755
20	98.6	8.0162
21	98.9	8.0406
22	99.4	8.0812
23	99.8	8.1137
24	99.9	8.1219
25	100	8.1300
26	100	8.1300

Impeller speed : 250 rpm

Air flow rate : 2 L/min

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	14.3	1.1626
2	27.4	2.2276
3	43.2	3.5122
4	54.9	4.4634
5	66	5.3658
6	72.2	5.8699
7	78.2	6.3577
8	83.2	6.7642
9	86.4	7.0243
10	89.6	7.2845
11	91.7	7.4552
12	93.8	7.6259
13	95.2	7.7398
14	96.2	7.8211
15	97.3	7.9105
16	97.9	7.9593
17	98.5	8.0081
18	98.9	8.0406
19	99.1	8.0568
20	99.5	8.0894
21	100	8.1300
22	100	8.1300

Impeller speed : 250 rpm

Air flow rate : 2.5 L/min

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	16	1.3008
2	30.9	2.5122
3	47	3.8211
4	59.5	4.8374
5	69.4	5.6422
6	77	6.2601
7	82.1	6.6747
8	86.7	7.0487
9	90	7.3170
10	92.6	7.5284
11	94.5	7.6829
12	96	7.8048
13	96.8	7.8698
14	97.8	7.9511
15	98.5	8.0081
16	98.8	8.0324
17	99.3	8.0731
18	99.6	8.0975
19	100	8.1300
20	100	8.1300

Impeller speed : 250 rpm

Air flow rate : 3 L/min

t(min)	DOT(%)	DOC(ppm)
0	0	0.0000
1	19.2	1.5610
2	35.3	2.8699
3	52.9	4.3008
4	65.5	5.3252
5	75.7	6.1544
6	82.6	6.7154
7	87.1	7.0812
8	91	7.3983
9	93.9	7.6341
10	95.6	7.7723
11	97.1	7.8942
12	98	7.9674
13	98.8	8.0324
14	99.3	8.0731
15	99.5	8.0894
16	100	8.1300
17	100	8.1300

APPENDIX C

MATLAB PROGRAMMING DATA

Effect of impeller speed on k_La and ka_p

N = 200rpm

Q=2L/min

M-file

```
function f=k(x)

f=(1.0813-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(2.2439-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(3.1544-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(4.0162-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(4.8455-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(5.5121-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(5.9105-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(6.2845-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(6.8292-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.1463-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.2601-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.5121-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.7154-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.9837-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(8.1137-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.5928



ans =

    0.2193    1.5236
```

N=250rpm

Q= 2 L/min

M-File

```
function f=k(x)

f=(1.0163-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(2.4146-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(3.6585-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(4.5853-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(5.3333-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(5.9999-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(6.4471-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(6.878-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.1463-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.4308-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.6097-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.7642-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.878-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.9755-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(8.0487-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.1189



ans =

    0.2585    1.5137
```

N=300rpm

Q= 2 L/min

M-file

```
function f=k(x)

f=(1.7723-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(3.4634-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(4.7479-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(5.8536-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(6.4959-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(6.9268-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(7.2682-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(7.5528-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.7154-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.8455-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.9186-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(8.0162-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(8.0406-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(8.0731-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(8.0894-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0309



ans =

    0.3393    3.2237
```

N=350rpm

Q= 2 L/min

M-file

```
function f=k(x)

f=(2.2927-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(4.2845-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(5.6829-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(6.4877-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(7.1707-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(7.4146-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(7.7398-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(7.8780-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.9837-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(8.0324-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(8.0731-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(8.1056-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0188



ans =

    0.4366    4.0770
```

N=400rpm

Q= 2 L/min

M-file

```
function f=k(x)

f=(2.8455-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(4.7073-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(6.1625-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(6.9837-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(7.4877-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(7.7479-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(7.9186-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(8.0243-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(8.0731-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(8.1219-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0588



ans =

    0.5056    5.7405
```

Effect of air flow rate on k_La and ka_p

Impeller speed : 250 rpm

Air flow rate : 1 L/min

M-file

```
function f=k(x)

f=(0.7642-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(1.5528-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(2.5467-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(3.3821-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(4.1870-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(4.8455-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(5.1951-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(5.6178-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(5.943-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(6.2601-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(6.5528-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(6.8861-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.0731-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.2601-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(7.382-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(7.4796-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(7.6097-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-
x(1)))))^2+(7.7072-(8.13-(8.13*x(1)*exp(-x(2)*18)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*18)/(x(2)-x(1)))))^2+(7.7642-(8.13-(8.13*x(1)*exp(-x(2)*19)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*19)/(x(2)-x(1)))))^2+(7.8211-(8.13-(8.13*x(1)*exp(-
x(2)*20)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*20)/(x(2)-x(1)))))^2+(7.878-(8.13-
(8.13*x(1)*exp(-x(2)*21)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*21)/(x(2)-
x(1)))))^2+(7.9105-(8.13-(8.13*x(1)*exp(-x(2)*22)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*22)/(x(2)-x(1)))))^2+(7.9674-(8.13-(8.13*x(1)*exp(-x(2)*23)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*23)/(x(2)-x(1)))))^2+(8.0081-(8.13-(8.13*x(1)*exp(-
x(2)*24)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*24)/(x(2)-x(1)))))^2+(8.0406-(8.13-
(8.13*x(1)*exp(-x(2)*25)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*25)/(x(2)-
x(1)))))^2+(8.0894-(8.13-(8.13*x(1)*exp(-x(2)*26)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*26)/(x(2)-x(1)))))^2+(8.1137-(8.13-(8.13*x(1)*exp(-x(2)*27)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*27)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*28)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*28)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*29)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*29)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.1340



ans =

    0.1645    1.5069
```

Impeller speed = 250 rpm

Air flow rate : 1.5 L/min

M-file

```
function f=k(x)

f=(0.9106-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(1.9106-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(3.0244-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(3.9349-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(4.7723-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(5.2764-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(5.7967-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(6.252-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(6.5934-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(6.8617-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.0731-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.2682-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.4715-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.5772-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(7.6991-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(7.7967-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(7.8617-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-
x(1)))))^2+(7.9511-(8.13-(8.13*x(1)*exp(-x(2)*18)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*18)/(x(2)-x(1)))))^2+(7.9755-(8.13-(8.13*x(1)*exp(-x(2)*19)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*19)/(x(2)-x(1)))))^2+(8.0162-(8.13-(8.13*x(1)*exp(-
x(2)*20)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*20)/(x(2)-x(1)))))^2+(8.0406-(8.13-
(8.13*x(1)*exp(-x(2)*21)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*21)/(x(2)-
x(1)))))^2+(8.0812-(8.13-(8.13*x(1)*exp(-x(2)*22)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*22)/(x(2)-x(1)))))^2+(8.1137-(8.13-(8.13*x(1)*exp(-x(2)*23)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*23)/(x(2)-x(1)))))^2+(8.1219-(8.13-(8.13*x(1)*exp(-
x(2)*24)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*24)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*25)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*25)/(x(2)-
x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-x(2)*26)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*26)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0763



ans =

    0.2007    1.5879
```

Impeller speed = 250 rpm

Air flow rate : 2 L/min

M-file

```
function f=k(x)

f=(1.1626-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(2.2276-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(3.5122-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(4.4634-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(5.3658-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(5.87-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(6.3577-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(6.7392-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.0243-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.2845-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.4552-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.6259-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.7398-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.8211-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(7.9105-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(7.9593-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.0081-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-
x(1)))))^2+(8.0406-(8.13-(8.13*x(1)*exp(-x(2)*18)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*18)/(x(2)-x(1)))))^2+(8.0568-(8.13-(8.13*x(1)*exp(-x(2)*19)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*19)/(x(2)-x(1)))))^2+(8.0894-(8.13-(8.13*x(1)*exp(-
x(2)*20)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*20)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*21)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*21)/(x(2)-
x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-x(2)*22)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*22)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0875



ans =

    0.2400    1.7479
```

Impeller speed = 250 rpm

Air flow rate : 2.5 L/min

M-file

```
function f=k(x)

f=(1.3008-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(2.5122-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(3.8211-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(4.8374-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(5.6422-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(6.2601-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(6.6747-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(7.0487-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.317-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.5284-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.6829-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.8048-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(7.8698-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(7.9511-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(8.0081-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(8.0324-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.0731-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-
x(1)))))^2+(8.0975-(8.13-(8.13*x(1)*exp(-x(2)*18)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*18)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-x(2)*19)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*19)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*20)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*20)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.0887



ans =

    0.2712    1.7887
```

Impeller speed = 250 rpm

Air flow rate : 3 L/min

M-file

```
function f=k(x)

f=(1.561-(8.13-(8.13*x(1)*exp(-x(2)*1)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*1)/(x(2)-
x(1)))))^2+(2.8699-(8.13-(8.13*x(1)*exp(-x(2)*2)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*2)/(x(2)-x(1)))))^2+(4.3008-(8.13-(8.13*x(1)*exp(-x(2)*3)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*3)/(x(2)-x(1)))))^2+(5.3252-(8.13-(8.13*x(1)*exp(-
x(2)*4)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*4)/(x(2)-x(1)))))^2+(6.1544-(8.13-
(8.13*x(1)*exp(-x(2)*5)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*5)/(x(2)-
x(1)))))^2+(6.7154-(8.13-(8.13*x(1)*exp(-x(2)*6)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*6)/(x(2)-x(1)))))^2+(7.0812-(8.13-(8.13*x(1)*exp(-x(2)*7)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*7)/(x(2)-x(1)))))^2+(7.3983-(8.13-(8.13*x(1)*exp(-
x(2)*8)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*8)/(x(2)-x(1)))))^2+(7.6341-(8.13-
(8.13*x(1)*exp(-x(2)*9)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*9)/(x(2)-
x(1)))))^2+(7.7723-(8.13-(8.13*x(1)*exp(-x(2)*10)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*10)/(x(2)-x(1)))))^2+(7.8942-(8.13-(8.13*x(1)*exp(-x(2)*11)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*11)/(x(2)-x(1)))))^2+(7.9674-(8.13-(8.13*x(1)*exp(-
x(2)*12)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*12)/(x(2)-x(1)))))^2+(8.0324-(8.13-
(8.13*x(1)*exp(-x(2)*13)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*13)/(x(2)-
x(1)))))^2+(8.0731-(8.13-(8.13*x(1)*exp(-x(2)*14)/(x(1)-x(2))+8.13*x(2)*exp(-
x(1)*14)/(x(2)-x(1)))))^2+(8.0894-(8.13-(8.13*x(1)*exp(-x(2)*15)/(x(1)-
x(2))+8.13*x(2)*exp(-x(1)*15)/(x(2)-x(1)))))^2+(8.13-(8.13-(8.13*x(1)*exp(-
x(2)*16)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*16)/(x(2)-x(1)))))^2+(8.13-(8.13-
(8.13*x(1)*exp(-x(2)*17)/(x(1)-x(2))+8.13*x(2)*exp(-x(1)*17)/(x(2)-x(1)))))^2
```

Command window

```
fminsearch('k',[-1,1])

f =

    0.1396



ans =

    0.3183    1.9269
```