# OXYGEN TRANSFER IN A STIRRED TANK 

by

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## ABSTRACT

Microbiological leaching of sulfide minerals in fermenters is believed to have commercial potential. The oxygen transfer rate has been assumed to be one of the most important factors affecting the leach rate. The mass-transfer rate at various solution $\mathrm{pH}^{\prime} \mathrm{s}$ was studied by using an unsteady gassing out process. The sulfite-oxidation process was also studied in an attempt to explain the absorption mechanism.

A 7.5 inch I.D. methyl methacrylate tank with 4 baffles and a 4-inch diameter paddle type impeller were used. The impeller was driven by a motor mounted on a dynamometer which allowed measurement of the power used in agitation. All the experiments were carried out under highly turbulent conditions and covered the liquid temperature range $25^{\circ} \mathrm{C}$ to $40^{\circ} \mathrm{C}$.

The results showed that pH had no effect on mass-transfer coefficient. The values of $\mathrm{K}_{\mathrm{L}}$ a increased as temperature increased. The relationship between $K_{L} a$, power input and superficial gas velocity was found to be of the form:

$$
K_{L} a=c(H P / V)^{x} \cdot\left(V_{S}\right)^{y}
$$

A comparison of the $K_{L}$ a observed in an unsteady gassing out process and that in a sulfite-oxidation process showed that the interfacial area/unit volume of liquid, a, is directly proportional to ( $V_{s}$ ) ${ }^{0.50}$ which coincides with Calderbank's result.

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NOMENCLATURE
interfacial area per unit volume, $f t^{2} / f t^{3}$
stoichiometric coefficients for reacting substance $B$ concentration of liquid, g moles/1
concentration of component in gas-liquid interface, $g$ moles/1 concentration of component in liquid which would be in equilibrium with partial pressure of component in the gas phase, g moles/l
concentration of reacting component in liquid, $g$ moles/1
molecular diffusivity of component $A, \mathrm{~cm}^{2} / \mathrm{hr}$ molecular diffusivity of component $B, \mathrm{~cm}^{2} / \mathrm{hr}$ impeller diameter, ft mean diameter of bubbles, cm gravitational constant, $\mathrm{cm} / \mathrm{sec}^{2}$

Henry's constant, g moles/1 atm gas hold up, \%
power input, horsepower/1000 gallons of liquid reaction rate constant, (conc) ${ }^{n-1} /(T I M E)^{n}$ mass transfer coefficient for gas film, $g$ moles $/ \mathrm{hr} \mathrm{cm}^{2} \mathrm{~atm}$ mass transfer coefficient for liquid, cm/hr over-all mass-transfer coefficient based on gas-film control, g moles/hr $\mathrm{cm}^{2} \mathrm{~atm}$
over-all mass-transfer coefficient based on liquid-film control, $\mathrm{cm} / \mathrm{hr}$
mass-transfer rate, $g$ moles/hr ft ${ }^{2}$
mass-transfer rate of species $A$ per unit area, $g$ moles/hr $f t^{2}$ mass-transfer rate of species $B^{\prime}$ per unit area, $g$ moles/hr $\mathrm{ft}^{2}$ agitation speed, rpm

Schmidt number, dimensionless
partial pressure in gas phase, atm

| $\mathrm{P}_{\mathbf{i}}$ | partial pressure of component at gas-liquid interface, at |
| :---: | :---: |
| $\mathrm{p} *$ | partial pressure of component which would be in equilibrium with concentration of liquid, atm |
| (Pg/V) | power input, erg/ml of liquid |
| Q | air flow rate, $\mathrm{ft}^{3} / \mathrm{hr}$ |
| t | time, hr |
| T | absolute temperature, ${ }^{\circ} \mathrm{K}$ |
| $\mathrm{V}_{S}$ | superficial gas velocity, ft/hr |
| $\mathrm{V}_{\mathrm{t}}$ | terminal superficial gas velocity, ft/hr |
| x | constant |
| $\mathrm{X}_{\mathrm{L}}$ | liquid-film thickness, cm |
| y | constant |
| $z$ | constant |
| $\sigma$ | surface tension, dyne/cm |
| $\rho_{c}$ | continuous phase viscosity, $\mathrm{g} / \mathrm{cm}^{3}$ |
| $\rho_{\text {d }}$ | dispersed phase viscosity, $\mathrm{g} / \mathrm{cm}^{3}$ |
| $\rho_{\mathrm{L}}$ | density of liquid, $\mathrm{g} / \mathrm{cm}^{3}$ |
| $\Delta \rho$ | density difference, $\mathrm{g} / \mathrm{cm}^{3}$ |
| ${ }^{\mu} \mathrm{c}$ | continuous phase viscosity, centipoise |
| H̄d | dispersed phase viscosity, centipoise |
| $\xi$ | reaction coefficient |

## INTRODUCTION

The bacterium, Thiobacillus ferrooxidans, is unique among bacteria in that it can oxidize ferrous iron and reduced sulfur compounds utilizing the energy so derived for its life processes. When metallic sulfides are oxidized, the release of associated metals into solution may be of considerable economic value. Microbiological leaching of metallic sulfides is currently used commercially in the leaching of waste dumps or abandoned areas of mines. It has a potential use in the leaching of sulfide concentrates utilizing tank type fermenters. In such a system a pulp of finely ground sulfide mineral in water would be aerated and agitated in a suitable vessel in the presence of $T$. ferrooxidans and nutrients essential for growth. The bacteria would oxidize the sulfide to sulfate releasing the associated metal ions into solution. A better understanding of the various factors influencing bacterial growth and the microbiological dissociation of sulfides may aid in improving the efficiency of the biological leaching process and lead to its increased utilization.

Oxygen transfer has been assumed to be one of the most important rate controlling factors, because the oxygen demand in oxidizing sulfide to sulfate is large. Moreover, the respiratory enzymes can utilize only dissolved oxygen and oxygen is so insoluble that at any time only a small reservoir exists in solution (at $35^{\circ} \mathrm{C}$ for example, water in equilibrium with air contains about 7 ppm of oxygen). The microorganisms are continuously drawing upon this reservoir and the supply must be replenished at a rate adequate to satisfy the demand in every portion of the culture fluid. Otherwise, there will be local or temporary depletion of oxygen which may damage the respiring cells.

The oxygen uptake rate for a resting cell suspension of $T$. ferrooxidans can be as high as 22,000 microliters of oxygen per milligram of cell nitrogen per hour, when oxidizing ferrous iron (1). When oxidizing chalcopyrite the oxygen uptake rate has been reported to be as high as $8,524 \mu 1 / \mathrm{mg}$ $\mathrm{N} / \mathrm{hr}$ for resting cell suspensions (2). However, when the organism was growing on chalcopyrite the maximum rate of oxygen utilization was $756 \mathrm{mg} / 1 / \mathrm{hr}$ (3).

Individual rate processes for the transfer of oxygen from the air to the respiratory enzyme system may be summarized as follows:
(1) Diffusional transfer from the air to the gas-1iquid interface.
(2) Diffusional transfer through the liquid film.
(3) Diffusional or convective transfer through the liquid to the cells.
(4) Diffusion through the film which surrounds the cell wall.
(5) Diffusion across the cell wall to the cell membrane.
(6) Chemical reaction with oxidizable substances through the mediation of the cell enzymes.

Each individual process must have a rate at least equal to the over-all rate; i.e., the over-all rate of the transfer can not exceed the lowest individual rate.

It has been assumed in most biological processes that the diffusional transfer of oxygen from the air to the liquid medium is a limiting factor in the rate of metabolism. Since the biological leaching of chalco-
pyrite is to be carried out at an optimum temperature of $35^{\circ} \mathrm{C}$ and at pH values of 1.0 to 3.0 , a knowledge of oxygen transfer rates under these conditions was required. Data at such pH values were not available prior to this study.

The object of this study was to attempt to obtain a correlation between over-all mass-transfer coefficient and the pH and temperature of the solution. At the same time the effects of various other parameters such as superficial velocity of the air and agitation speed were evaluated. This knowledge should allow one to predict the maximum leach rates possible if oxygen transfer is the rate limiting step in the microbiological oxidation of sulfides.

## SURVEY OF LITERATURE

## A. Over-all Mass Transfer Coefficient

The rate of dissolution of oxygen is proportional to the depletion of dissolved oxygen in the liquid. The rate is also proportional to the interfacial area, and therefore, one may write for a unit volume of culture fluid

$$
\begin{aligned}
& \text { rate of absorption, } N_{A}=k_{G} a\left(P-P_{i}\right)=k_{L} a\left(C_{i}-C\right) \quad--(1) \\
& N_{\dot{A}}=K_{L} a\left(C^{*}-C\right)=K_{G} a\left(P-P^{*}\right) \quad--(2)
\end{aligned}
$$

The product of $K_{L}$ and a can be found indirectly through a knowledge of $C^{*}$ (by Henry's Law), and $C$ (by measurement) and the rate of absorption $N_{A}$ (by measurement). Since, in a steady state, the rate of absorption exactly equals the rate of demand

$$
\begin{equation*}
K_{L} a=N_{A} /\left(C^{*}-C\right) \tag{3}
\end{equation*}
$$

$K_{L}$ a provides an over-all measure of the gas absorbing capacity of any fermenter. It is in fact the only practical way to characterize the performance of laboratory or industrial devices.

## B. Controlling Resistances

The proportionality constant $K_{L}$ in equation (2) is the over-all mass transfer coefficient. Its reciprocal, $1 / K_{L}$, an over-all resistance, is equal to the sum of the separate resistances residing in the gas film, the interface and the liquid film.

Chiang and Toor (4) and Scriven and Pigford (5) found in laminar liquid jet experiments that little interfacial resistance existed. Therefore the over-all resistance, as shown by equation (4)

$$
\begin{equation*}
1 / K_{L} a=1 / k_{L} a+1 / H k_{G} a \tag{4}
\end{equation*}
$$

indicates that, when $k_{G} a$ is large compared to $k_{L} a$, the term $1 / k_{G}$ a is negligible compared to the term $1 / \mathrm{k}_{\mathrm{L}}$ a and the over-all transfer coefficient approximately equals the liquid phase coefficient. In such a case, it is said that the liquid phase constitutes the controlling resistance of the operation.

Experiments have shown that liquid film resistance was controlling for oxygen transfer in bubble aeration (6). Even under conditions of minimum mass-transfer rate in the gas film, Calderbank (7) showed that the mass-transfer coeffient of the gas film was at least 44 times higher than that of the liquid film.

## C. Sulfite-Oxidation Process

Oxygen absorption rates can be determined practically in several ways, among which the sulfite oxidation process of Cooper et al (8) is used perhaps the most frequently for aeration rate studies. Basically, this method depends on the oxidation of sulfite to sulfate by oxygen in the presence of a catalyst according to equation (5).

$$
\begin{equation*}
\mathrm{SO}_{3}^{\overline{\overline{3}}}+\frac{1 / 2 \mathrm{O}_{2}}{\text { Catalyst }} \mathrm{Cu}^{++} \mathrm{SO}_{4}^{=} \tag{5}
\end{equation*}
$$

The reaction is considered to be zero order with respect to both sulfite and sulfate concentrations and the reaction rate is considered to be sufficiently fast so that it is not the rate limiting step.

In Cooper's procedure a sulfite solution is aerated for a measured time; a known excess of iodine is then added to react with the unoxidized sulfite and the unreacted iodine is titrated with sodium thiosulfate. By calculation, the amount of sulfite converted to sulfate may be determined; and hence, the amount of oxygen going into solution during the measured time interval can be calculated.

At any time the amount of unreacted, dissolved oxygen in the solution can be assumed to be zero because the chemical reaction rate is much faster than the rate of solution of oxygen. Therefore when $C=0$, equation (3) becomes

$$
\begin{equation*}
\mathrm{K}_{\mathrm{L}} \mathrm{a}=\mathrm{N}_{\mathrm{A}} / \mathrm{C}^{*} \tag{6}
\end{equation*}
$$

The saturation values $\left(C^{*}\right)$ for oxygen in sulfite solutions can be calculated from the data of MacArthur (9). In very dilute solutions the values can be assumed to be the same as those in pure water. The rate of absorption $\left(\mathrm{N}_{\mathrm{A}}\right)$ is determined experimentally and hence, values of $\mathrm{K}_{\mathrm{L}}$ a are obtained.

Miyamoto $(10,11,12,13)$ has presented a comprehensive study of the sulfite-oxygen system. He found the absorption rate to be directly proportional to oxygen partial pressure and interfacial area. It increased with temperature, exhibiting an activation energy of approximately 12.5 kcal/mole.

Fuller and Crist (14) later made a very careful study of the reaction rate. The uncatalyzed reaction rate was found to be first-order with respect to sulfite. Westerterp et al (15) found that the copper-catalyzed sulfite-oxygen reaction was zero-order with respect to sulfite concentration and first-order with respect to the dissolved oxygen concentration.

Phillips and Johnson (16) measured the effect of oxygen partial pressure on the rate of oxidation of copper- and cobalt-catalyzed sulfite solution in both sparged and unsparged cylinders. They found that in the sparged system the rate of oxidation varied directly with oxygen partial pressure. For the unsparged cylinder, at low turbulence levels, the rate of oxidation varied as the 1.5 power of the partial pressure of oxygen, and at high turbulence levels it varied directly, as for the sparged system. They derived one equation for low turbulence absorption where it was assumed that all of the oxygen-sulfite reaction occurred in the stagnant liquid film. This equation was second-order with respect to oxygen concentration and first-order with respect to sulfite concentration. A second equation was given for highly turbulent conditions in which it was assumed that the chemical reaction occurred in the bulk of the liquid. Under these conditions the transfer rate was independent of sulfite concentration and varied directly with oxygen partial pressure. The oxygen uptake rate determined under these highly turbulent conditions was considered to be the maximum rate at which oxygen could be transferred from the gas phase into a fermentation liquid.

Murphy et al (17) investigated aeration in tower-type fermenters in which air was introduced at the base of the fermenter through porous discs. They found that the rate of oxidation of copper-catalyzed sulfite solutions was strongly dependent on the total amount of sulfite and sulfate present, and not on the concentration of sulfite alone. For initial concentration of sulfite in the range 0.10 to 0.20 N the rate was highly dependent on the concentration. They attributed this to the dependence of bubble size on normality of the solution.

Roxburgh (18) studied the effect of different catalysts on the oxidation of sodium sulfite solutions in several different types of equipment and showed radical differences in rates between copper-, cobalt-, nickel-, and iron-catalyzed systems. He also observed that the rate found for any single catalyst system depended to an appreciable extent on the pH of the sulfite solution.

Fuller and Crist (14) found that the rate of sulfite oxidation was independent of the pH between 8.2 and 8.8 but decreased in a complicated way between 3.2 and 5.9. This was accounted for by assuming that the rate was dependent on the sulfite ion concentration and the square root of the hydrogen ion concentration, but was independent of the acid sulfite ion concentration. They also found that the reaction system was very sensitive to both positive and negative catalysis. However, increased cupric ion concentration had no effect on the reaction rate at concentrations above $10^{-4} \mathrm{M}$.

Robinson and Engel (19) found that the copper-catalyzed sulfiteoxygen reaction rate was even slower than the uncatalyzed reaction rate: They recommended the use of a cobalt catalyst instead of.a copper catalyst.

Carpani and Roxburg (20) found that the rate of oxidation of copper-catalyzed sulfite solutions decreased as agitation was increased in an unbaffled stirred jar in which oxygen could enter the liquid only. through the horizontal air-liquid interface. This was contradictory to the results they found for oxygen transfer to water and sodium chloride solutions, where transfer rates increased with increasing agitation. Schultz and Gaden (21) had previously reported a similar phenomenon, and explained it on the basis of a chain mechanism for the oxidation of sulfite, with the requirement of an induction period for the concentration of intermediates to build up.

Phillips (22), using three horizontal fermenters, rotating at peripheral velocities in excess of $100 \mathrm{~cm} / \mathrm{sec}$, found that the rate of oxygen transfer to catalyzed sodium sulfite solutions was similar to those for fermentations. However, at peripheral velocities below $100 \mathrm{~cm} / \mathrm{sec}$ some unknown factors apparently affected the reaction kinetics and the resulting transfer rates were considerably higher than those observed for oxygen transfer to fermentations.

Carpani and Roxburgh, and Phillips were not dealing with the mass transfer from air bubbles to liquid but with transfer from air to flat liquid surfaces. Apparently, this kind of transfer was less affected than air bubble-1iquid transfer by the properties of the liquid (23).

The kinetics and mechanism of the oxidation of sulfite have been extensively studied and mechanisms have been proposed by several authors, the most noteworthy being Laidler (24), who postulated a free radical ion intermediate. Nevertheless, many questions concerning this reaction remain unanswered. The sulfite-oxidation process has also been found not suitable for comparison of the over-all mass-transfer rate at low pH values, because as shown by Fuller and Crist (14), the rate of the sulfite-oxygen reaction was so slow at low pH values that it became the rate limiting step.

However, the dependence of the reaction rate of the copper-catalyzed sulfite-oxygen reaction on the unreacted sulfite concentration was studied as part of this thesis. The data were compared with those obtained by an unsteady gassing out process. An attempt was made to explain the absorption mechanism in the sulfite-oxidation process.

## D. Unsteady Gassing Out Process

A gassing out process appeared to be the only way of measuring $K_{L}$ a in a liquid medium at low pH . Under these conditions of low pH dissolved oxygen can be determined either by the Modified Winkler Method Appendix (I) or by the use of an oxygen analyser. Saṭuration values can be determined at any pH. Data from International Critical tables (25) showed that when air was brought into contact with 0.5 N sulfuric acid, the saturation oxygen concentration was 7.05 ppm at $25^{\circ} \mathrm{C}$, the value in pure water under the same condition is 7.50 ppm .

The mass transfer coefficient can be calculated from the integral form of the rate equation either graphically or numerically,

$$
\begin{equation*}
\frac{d C}{d t}=K_{L} a \quad\left(C^{*}-C\right) \tag{7}
\end{equation*}
$$

on integration

$$
\begin{equation*}
K_{L} a=\frac{1}{\left(t_{2}-t_{1}\right)} \ln \frac{\left(C^{*}-C_{1}\right)}{\left(C^{*}-C_{2}\right)} \tag{8}
\end{equation*}
$$

E. Mass Transfer with Chemical Reaction (Sulfite-Oxidation Process) and without Chemical Reaction (Unsteady Gassing Out Process)

Theoretical equations for simultaneous diffusion and chemical reaction in the liquid phase have been derived. The first attempt was made by Hatta (26). He applied Lewis and Whitman's two film theory (27) to the absorption of carbon dioxide in alkali solution. Derivations based on the unsteady-state theories of Higbie and Danckwerts have been given in many papers (28). From a physical point of view, the unsteady-state theories are probably more correct, but all these models give qualitatively the same
results as the film theory (29). Because of this and the simplicity of the film theory, we shall deal with it exclusively.

The film theory assumes that the resistance to diffusion is concentrated in both the gas and liquid films which are adjacent to the gas-liquid interface, that the concentration profile is independent of time, i.e., at steady state, and that instantaneous equilibrium between $\mathrm{P}_{i}$ and $\mathrm{C}_{i}$ is established as soon as the gas contacts the liquid (Figure 1). Figure 1 shows the concentration profiles in the two films.
(1) Infinitely Fast Reaction

When the reaction is infinitely fast according to the equation,

$$
\mathrm{A} \text { (gas phase) }+\mathrm{b} \text { B (liquid phase) } \longrightarrow \text { product }-- \text { (9) }
$$

A will dissolve and react immediately with $B$ at the phase boundary. The product will begin to diffuse toward the main body of liquid. The concentration profiles for this case would be as shown in Figure 2.

In a unit contact area, the diffusion rate of $A$ and $B$ in the liquid phase can be expressed as:

$$
\begin{align*}
& \mathrm{N}_{\mathrm{A}}^{\mathrm{l}}=\frac{\mathrm{D}_{\mathrm{A}}}{\mathrm{fx}_{\mathrm{L}}} \quad\left(\mathrm{C}_{\mathrm{i}}-0\right)  \tag{10}\\
& \mathrm{N}_{\mathrm{B}}^{1}=\frac{\mathrm{D}_{\mathrm{B}}}{(1-\mathrm{f}) \mathrm{x}_{\mathrm{L}}} \quad\left(\mathrm{C}_{\mathrm{B}}-0\right)=\frac{\mathrm{SD}_{A}}{(1-f) \mathrm{x}_{\mathrm{L}}} C_{B}
\end{align*}
$$

where $S=D_{B} / D_{A}$ and $f$ is as shown in Figure 2.


FIG 1. CONCENTRATION PROFILES ACROSS A GASLIQUiD INTERFACE. THE VALUE OF PI IS INEQULIBRIUM WITH THAT OF CI, THE CONCENTRATIONS ( C AND P ) WITHIN THE EFFECTIVE FLMS CHANGE LINEARLY WITH DISTANCE FROM THE INTERPHASE


FIG 2. SKETCH OF GRADIENTS IN DOUBLE FILM WITH IRREVERSIBLE INSTANTANEOUS REACTION FOLOUNNG ABSORPTION

At steady state $N_{B}{ }^{l}=N_{A}{ }^{l} b$, therefore by combining equation (10) and (11), solving for $f$ and substituting in equation (10),

$$
\begin{equation*}
N_{A}^{1}=\frac{D_{A}}{x_{L}} C_{i}\left(1+\frac{S}{b} \frac{C_{B}}{C_{i}}\right)=k_{L} C_{i}\left(1+\frac{S}{b} \frac{C_{B}}{C_{i}}\right)- \tag{12}
\end{equation*}
$$

Since $C_{i}=H P_{i}$, equation (12) can be rearranged as:

$$
\begin{equation*}
N_{A}^{1}=\frac{P_{A}+\mathrm{S} \mathrm{C}_{B} / \mathrm{b} \cdot \mathrm{H}}{1 / \mathrm{k}_{\mathrm{G}}+1 / \mathrm{H} k_{\mathrm{L}}}=\frac{\mathrm{C}^{*}+\mathrm{S} \mathrm{C}_{B} / \mathrm{b}}{\mathrm{H} / \mathrm{k}_{\mathrm{G}}+1 / \mathrm{k}_{\mathrm{L}}} \tag{13}
\end{equation*}
$$

where $C^{*}=\mathrm{HP}_{\mathrm{A}}$
when there is no chemical reaction

$$
\mathrm{N}_{\mathrm{A}}^{\mathrm{l}}=\mathrm{k}_{\mathrm{L}} \mathrm{C}_{\mathrm{i}}
$$

The reaction coefficient

$$
\begin{equation*}
\xi=\frac{\mathrm{N}_{\mathrm{A}}^{1} \text { with reaction }}{\mathrm{N}_{\mathrm{A}}^{1} \text { without reaction }}=1+\mathrm{qS} \tag{14}
\end{equation*}
$$

where, $q=C_{B} / b C_{i}$

The derivation of equation (13) follows that of Hatta (26), who was interested in the batch absorption of $\mathrm{CO}_{2}$ by KOH solutions.
(2) Irreversible-Pseudo-First-Order-Slow-Reaction

If the reaction is a pseudo-first-order reaction and the reactant in the liquid is insoluble in the gas, i.e., the zone of reaction is in the liquid film, the diffusion rate $=$ reaction rate (30). Therefore,

$$
\begin{equation*}
-D \frac{d^{2} C_{A}}{d x^{2}}=k_{1} C_{A} \tag{15}
\end{equation*}
$$

The boundary conditions are:

$$
\begin{array}{ll}
\mathrm{x}=\mathrm{o} & \mathrm{C}_{\mathrm{A}}=\mathrm{C}_{\mathrm{i}} \\
\mathrm{x}=\mathrm{x}_{\mathrm{L}} & \mathrm{C}_{\mathrm{A}}=\mathrm{C}_{\mathrm{L}} \tag{16}
\end{array}
$$

Solution of (15) and (16) gives:

$$
\begin{aligned}
& N_{A}|x=0=-D| \frac{d C_{A}}{d x} \left\lvert\, x=0=\frac{D C_{i}}{x_{L}}\left(\frac{b_{1} \cosh b_{1}-b_{1} \Gamma}{\sinh \cdot b_{1}}\right)--(17)\right. \\
& \left(N_{A}\right) \text { no reaction }=-D\left|\frac{d C_{A}}{d x}\right|_{x=0} \text { no reaction }=\frac{D C_{i}}{x_{L}}(1-\Gamma)--(18)
\end{aligned}
$$

where $b_{1}=\sqrt{k_{1} x_{L}{ }^{2} / D}, \quad \Gamma=C_{L} / C_{i}$

In the special case where the concentration of $A$ in the main body of liquid is low, equation (17) may be written

$$
\begin{equation*}
N_{A} \left\lvert\, x=0=\frac{b D \cdot\left(C_{i}-C_{L}\right)}{x_{L}}\right. \tag{19}
\end{equation*}
$$

where $\mathrm{b}_{1}=\frac{\mathrm{b}_{1}}{\tanh \mathrm{~b}_{1}}>1.0$

$$
\begin{equation*}
\left(K_{L}\right) \text { reaction }=\frac{N_{A} \mid x=0}{\left(C_{i}-C_{L}\right)}=b \frac{D}{x_{L}} \tag{20}
\end{equation*}
$$

$$
\begin{equation*}
\left(K_{L}\right) \text { no reaction }=\frac{D}{x_{L}} \tag{21}
\end{equation*}
$$

The reaction coefficient

$$
\begin{equation*}
\xi=\frac{\left(K_{L}\right) \text { reaction }}{\left(K_{L}\right) \text { no reaction }}=\frac{b_{1}}{\tanh b_{1}}>1.0 \tag{22}
\end{equation*}
$$

The ratio of mass-transfer coefficients is always greater than 1.0. It depends on the reaction rate constant, film thickness and diffusivity. If $b_{l}>5, \xi$ nearly equals $b_{1}$, and it equals $b$. Therefore the absorption rate becomes

$$
\begin{equation*}
\mathrm{N}_{\mathrm{A}}=\sqrt{\mathrm{k}_{1} \mathrm{D}} \mathrm{C}_{\mathrm{i}} \tag{23}
\end{equation*}
$$

With a very fast reaction the absorption rate will be a constant, which is independent of the film thickness. It should be pointed out that the magnitudes of $k_{G}, k_{L}, H, C_{i}, C^{*}$ in the above equations are different to those for purely physical absorption, because the properties should be adjusted to allow for the presence of salts. But with very dilute solutions, we can assume that all the values are the same in both situations.

## F. Factors Affecting the Values of Mass-Transfer Coefficients

(1) Effect of Liquid Temperature on $K_{L}$ a

Robinson and Enge1 (19) made a series of runs over the liquid temperature range $65^{\circ}$ to $105^{\circ} \mathrm{F}$, with a sipgle-stage cycled apparatus and found that the temperature dependence of the over-all mass-transfer coefficient was not significantly greater than the normal experimental scatter.
$0^{\prime}$ Connor (31) studied the effect of temperature on the value of $K_{L} a$ and found the following relationship to exist:

$$
\begin{equation*}
\frac{K_{L} a\left(t_{1}\right)}{K_{L} a\left(t_{2}\right)}=\sqrt{\frac{T_{1} \mu_{2}}{T_{2} \mu_{1}}} \tag{24}
\end{equation*}
$$

This equation was derived on the basis of oxygen transfer during bubble aeration of an activated-sludge process for the biological treatment of waste.

Yoshida (32) found that in oxygen-water contactors, the effect of temperature on $K_{L}$ a was slight. At $20^{\circ}$ and $40^{\circ} \mathrm{C}$ values of $K_{L}$ a coincided over the entire experimental range of agitator speeds 100 to 600 rpm , indicating that at those two temperatures the effect of temperature on $K_{L}$ and on the interfacial area, $a$, offset each other. The values of $K_{L} a$ at $7^{\circ} C$ were found to be about $25 \%$ lower than at $20^{\circ} \mathrm{C}$ for the same agitator speed.

As far as fermentation is concerned only a narrow range of temperature is of any interest. Thus the present experiments covered a liquid temperature range from $25^{\circ} \mathrm{C}$ to $40^{\circ} \mathrm{C}$.
(2) Effect of Liquid Depth on $K$ a

Yoshida (32) used oxygen-water contactors and found that the effect of the ratio of liquid depth to tank diameter on $K_{L}$ a was negligible for ratios less than 1.0 , but it becomes appreciable for values above unity, e.g., at 1.4 , values of $K_{L}$ a are reduced about $30 \%$ from those at unity.

An empirical factor ( $\mathrm{f}_{\mathrm{c}}$ ) was presented in graphical form by Cooper et al (8) to correct for the case in which the ratio of liquid height to vessel diameter, $H_{L} / D_{t}$, deviates from 1.0.
$K_{L} a=f_{c}\left(K_{L} a\right)_{H_{L}} / D_{t}=1: 0$.
e.g., when $H_{L} / D_{t}=2.0$
$\mathrm{f}_{\mathrm{c}} \quad \doteqdot \quad 1.45$
Bewtra and Nicholas (33) performed aeration tests in a 4-foot deep aeration tank and found a linear relationship between percent oxygen absorbed from the inlet air stream and depth. The oxygen absorption efficiency increased as the water depth increased. To evaluate the contribution of surface aeration and transfer during formation, they extended their plot of absorption efficiency versus depth to zero depth and considered the intercept on the vertical axis as the contribution of oxygen transfer occurring during bubble formation and at the surface. They assumed that gas transfer occurring at bubble formation and the surface was independent of depth. Aiba et al (34) made the same assumption when they extended a plot of $K_{L}$ a versus depth to zero depth in order to evaluate the contribution of transfer during bubble formation and at the surface.

Radford (35) found that in a 7.5-inch I.D. 1ucite column the overall transfer coefficient, $\mathrm{K}_{\mathrm{L}} \mathrm{a}$, was essentially independent of water depth from 1 to 7 feet at an air flow rate of $2300 \mathrm{ml} / \mathrm{min}$. There was only a slight variation in $\mathrm{K}_{\mathrm{L}}$ a with depth at a flow rate of $1150 \mathrm{ml} / \mathrm{min}$.

Obviously, the oxygen absorption efficiency will be increased as the water depth is increased, because of the longer retention time of air bubbles in the water at greater depths. On the other hand, the effect of liquid depth on the values of $\mathrm{K}_{\mathrm{L}}$ a does not appear straightforward. Yoshida's (32) and Cooper's (8) results contradict each other. This present work does not resolve this conflict because liquid depth was maintained at a constant level. Since the true oxygen transfer rate from the air bubbles to the liquid must be calculated by subtracting the amount of oxygen transfer by surface aeration from the total aeration rate, the magnitude of surface aeration should be studied.

According to equation (3)

$$
\begin{equation*}
K_{L} a=N_{A} /\left(C^{*}-C\right) \tag{3}
\end{equation*}
$$

where $C^{*}$ is the concentration of oxygen in the liquid that would be in equilibrium with the partial pressure of oxygen in the air. However, there is some debate over what value of $\left(C^{*}-C\right)$ should be used. Cooper et al (8) have assumed $C=0$ and have based the concentration driving force on $C$ * in equilibrium with the inlet gas stream. But when the liquid medium is perfectly mixed, the proper driving force would be based on $C$ * of the outlet gas stream. If liquid depth in the tank is comparably high, a logarithmic mean driving force based on $C^{*}$ at the gas inlet and $C^{*}$ at , the gas outlet should be used.
(3) Effect of Gas Superficial Velocity and Power Input

To correlate the mass-transfer coefficients in agitated vessels to the pertinent operating variables, equations of the following form are often encountered:

$$
\begin{equation*}
\mathrm{K}_{\mathrm{L}} \mathrm{a} \quad \alpha \quad(\mathrm{HP} / \mathrm{V})^{\mathrm{x}}\left(\mathrm{~V}_{\mathrm{s}}\right)^{\mathrm{y}} \tag{26}
\end{equation*}
$$

or

$$
\begin{equation*}
\mathrm{K}_{\mathrm{L}} \quad \alpha \quad \alpha \quad(\mathrm{~N})^{\mathrm{z}} \quad\left(\mathrm{~V}_{\mathrm{S}}\right)^{\mathrm{y}} \tag{27}
\end{equation*}
$$

The relationship between $K_{L} a$ and power input at constant gas flow rate obtained by Cooper (8) for a vaned-disc impeller was:

$$
\begin{equation*}
K_{\mathrm{L}} \mathrm{a} \quad \alpha \quad(\mathrm{HP} / \mathrm{V})^{0.95}\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.67} \tag{28}
\end{equation*}
$$

whereas Augenstein and Wong (36) showed that the following relationship existed:

$$
\begin{equation*}
\mathrm{K}_{\mathrm{L}} \mathrm{a} \quad \alpha \quad(\mathrm{HP} / \mathrm{V}){ }_{\left(\mathrm{V}_{\mathrm{s}}\right)}^{0.85} \text { for (HP/V)<40.0 } \tag{29}
\end{equation*}
$$

However, when the agitator power was increased above $40 \mathrm{HP} / 1000$ gallons the dependence of $\mathrm{K}_{\mathrm{L}}$ a on power input was found to be drastically reduced. Thus

$$
\mathrm{K}_{\mathrm{L}} \mathrm{a} \quad \alpha \quad(\mathrm{HP} / \mathrm{V})^{0.57}\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.2} \text { for }(\mathrm{HP} / \mathrm{V})>40.0 \quad-\text { (30) }
$$

the latter authors postulated that for power inputs greater than $40 \mathrm{HP} / 1000$ gallons the increase in the over-all mass-transfer coefficient was due to a combination of a decrease in the average bubble size and possibly an increase in the $K_{L}$ arising from an increase in the velocity of the bubbles.

The same authors showed that for gas flow rates equivalent to a superficial gas velocity of $39.6 \mathrm{ft} / \mathrm{hr}$, the mass-transfer coefficient was proportional only to the 0.2 power of the gas velocity. A further increase in the gas flow had no effect on the mass transfer coefficient. These findings were in general agreement with the results reported by Westerterp et al (15).

It has been recommended (37) that equation 28 be applied under the following conditions ( $\mathrm{V}_{\mathrm{s}}<90 \mathrm{~m} / \mathrm{hr}$ ) for one set of impellers and $\left(V_{s}<150 \mathrm{~m} / \mathrm{hr}\right)$ for two sets of impellers, provided:

$$
(\mathrm{HP} / \mathrm{V})>0.1 \mathrm{HP} / \mathrm{m}^{3} \text { and } \mathrm{H}_{\mathrm{L}} / \mathrm{D}_{\mathrm{t}}=1.0
$$

For a paddle impeller

$$
\begin{equation*}
\mathrm{K}_{\mathrm{L}} \mathrm{a} \quad \alpha(\mathrm{HP} / \mathrm{V})^{0.53}\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.67} \tag{3I}
\end{equation*}
$$

provided:

$$
\mathrm{V}_{\mathrm{s}}<21.0 \mathrm{~m} / \mathrm{hr}, \quad \mathrm{HP} / \mathrm{V}>0.06 \mathrm{HP} / \mathrm{m}^{3}, \quad \mathrm{H}_{\mathrm{L}} / \mathrm{D}_{\mathrm{t}}=1.0
$$

Using the light-transmission technique, Calderbank (7,38) found the mean diameter for dispersions of gas bubbles in solutions of electrolytes to be:

$$
\mathrm{D}_{\mathrm{P}}=2.25 \frac{\sigma^{0.6}}{(\mathrm{Pg} / \mathrm{V})^{0.4} \rho_{\mathrm{c}}^{0.2}} \mathrm{H}_{0}^{0.40} \frac{\left(\mu_{\mathrm{d}}\right)^{0.25}}{\left(\mu_{\mathrm{c}}\right)}--(32)
$$

For dispersions of gas bubbles in aqueous solutions of alcohols he found:

$$
\begin{equation*}
\mathrm{D}_{\mathrm{P}}=1.90 \frac{0^{0.6}}{(\mathrm{Pg} / \mathrm{V})^{0.4} \rho_{\mathrm{c}}^{0.2}} \quad \mathrm{H}_{\mathrm{o}}^{0.65}\left(\frac{\mu_{\mathrm{d}}}{\mu_{\mathrm{c}}}\right)^{0.25} \tag{33}
\end{equation*}
$$

The bubble sizes in pure liquids were greater than in electrolytes. Calderbank explained this could be attributed to the greater ease of bubble coalescence in the pure liquids. He concluded that the bubbles close to the tip of the impeller were not the mean values for the whole tank contents and proposed the equation:

$$
\begin{equation*}
a=1.44 \frac{(\mathrm{Pg} / \mathrm{V})^{0.4} \rho_{c}^{0.2}}{\sigma^{0.6}}\left(\frac{\mathrm{v}_{\mathrm{s}}}{\mathrm{v}_{\mathrm{t}}}\right)^{0.5} \tag{34}
\end{equation*}
$$

He also found two correlations for liquid-phase mass-transfer coefficients for the different sizes of the bubbles. For average bubble diameter greater than about 2.5 mm :

$$
\begin{equation*}
\mathrm{k}_{\mathrm{L}}\left(\mathrm{~N}_{\mathrm{sc}}\right)^{0.5}=0.42\left(\frac{\Delta \rho_{\mu_{c^{2}}}}{\rho_{\mathrm{c}}{ }^{2}}\right)^{1 / 3} \tag{35}
\end{equation*}
$$

For average bubble diameter less than 2.5 mm :

$$
\begin{equation*}
\mathrm{k}_{\mathrm{L}}\left(\mathrm{~N}_{\mathrm{Sc}}\right)^{2 / 3}=0.31\left(\frac{\Delta \rho \cdot \mu_{\mathrm{c}} \mathrm{~g}}{\rho_{\mathrm{c}}^{2}}\right)^{1 / 3} \tag{36}
\end{equation*}
$$

Both equations show that $\mathrm{k}_{\mathrm{L}}$ is independent of bubble size and rising velocity and depends only on the physical properties of the system.
(4) Other Factors

The presence of organic substances, solid particles, cells, etc., may affect the values of $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ but they will not be examined as part of this thesis.
G. Effect of Aeration Rate on Pöwer Consumption

The power consumption for an impeller operating at various speeds in a liquid can be predicted from published power number versus Reynold's number plots (39). However, similar plots are not available for gassed systems, since aeration causes changes in the liquid properties, (density and viscosity) in a manner which is not easily characterized.

Ohyama and Endoh (40) have correlated $\mathrm{Pg} / \mathrm{Po}$, with aeration number Q/ $\left(\mathrm{ND}_{\mathrm{I}}{ }^{3}\right)$ where:
$\frac{\mathrm{Pg}}{\text { Po }}=\frac{\text { Power requirement in gassed system }}{\text { Power requirement without gassing }} \quad$ (Dimensionless)
$\frac{Q}{\left(N D_{I}{ }^{3}\right)}=\frac{Q / D_{I}{ }^{2}}{\left(N D_{I}\right)}=\frac{\text { Velocity of air through sectional area of tank }}{\text { Tip velocity of impeller }}$ (Dimensionless)

The resulting curves were independent of physical properties of the liquids, but were dependent on the types of impellers and the geometrical ratio of the agitated vessels.

Calderbank (38) and Moo-Young (41) used flat-blade impellers in aerated mixing vessels and found that the curves of $\mathrm{Pg} / \mathrm{Po} v \mathrm{v} . \mathrm{Q} /\left(\mathrm{ND}_{\mathrm{I}}{ }^{3}\right.$ ) were independent of the properties of the liquids used.

Aiba (42) reached the opposite conclusion since his curves of $\operatorname{Pg} / \mathrm{Po}$ vs. $\mathrm{Q} /\left(\mathrm{ND}_{\mathrm{I}}{ }^{3}\right)$ were dependent on the viscosity of the liquid for both Newtonian and non-Newtonian liquids.

## EXPERIMENTAL DETAILS

## I. APPARATUS

A. General

The apparatus consisted of a reactor, an impeller, an agitator with dynamometer, a nozzle, three saturators, a heating coil, a water bath, an oxygen analyser with electrode, a recorder, a mercury manometer, thermocouples, a thermometer, a variable flow meter, a needle valve, a temperature regulator, a relay, a tachometer, a liquid nitrogen cylinder and normal titration equipment.

## B. Detail

(1) Reactor

The reactor was a cylindrical tank made of methyl methacrylate polymer, $7 \frac{1}{2}$ inches I.D. and 24 inches high with an open top. Four baffles, each one-tenth of the tank diameter and extending the full depth of the tank, were symmetrically attached to the internal wall. A steel rule was attached to the tank wall as shown in Figure 3.
(2) Impeller

The stainless steel impeller had six straight, flat-blades, 4 inches in diameter, of the paddle type. It was located one impeller diameter above the bottom of the tank (Figure 3).
(3) Agitator with Dynamometer

A quarter horsepower BENCO model ELB experimental agitator with dynamometer accessory was used. Fastened to the motor, whichrrested on a nearly frictionless ball-bearing, was a rod that was attached to a spring balance. The displacement of the spring, due to the action of the rotating shaft could then be measured. The motor had an output speed of 0 to 1100 rpm .

FIGURE 3. SCHEMATIC DRAWING OF REACTOR
(4) Nozzle

A stainless steel nozzle, having 18, 0.0260 in. I.D. holes (Figure 4), was mounted 1 inch below the impeller.
(5) Saturators

Three 1 \& pyrex Erlenmeyer flasks filled with water were connected in series as an air saturator.
(6) Heating Coil

Air was preheated to the desired temperature by passing through an externally heated coil made of $3 / 8^{\prime \prime}$ O.D. copper tubing.
( 7 ) Water Bath
The reactor, saturators and heating coil were kept in a $3^{\prime} \mathrm{x} 2^{\prime} \mathrm{x}$ $2 \frac{1}{2}{ }^{\prime}$ galvanized iron water bath. A one KN. heater activated by a mercury thermoregulator, maintained the desired temperature ( $\pm 0.5^{\circ} \mathrm{C}$ ). An agitator driven by a $1 / 20$ horsepower motor was used to circulate the water.
(8) Oxygen Analyzer with Electrode

A Beckman 39065 polarographic oxygen electrode was mounted through on the side of the reactor, two inches from the bottom (Figure 3). It was placed at an angle of nearly 15 degrees from the horizontal, in order to prevent any air bubbles from contacting the sensing membrane. A thermistor is built into this electrode to compensate for variations in diffusion rate through the teflon membrane, due to temperature changes. According to the manufacturer this temperature compensation reduced errors to less than $\pm 5 \%$ of the reading over the $15^{\circ} \mathrm{C}$ range. The accuracy of the electrode at constant temperature was $1 \%$ full scale.


FIGURE 4. SCHEMATIC DRAWNG OF NOZZLE

A Beckman Model 777 Laboratory Oxygen Analyser was connected to the electrode to determine the dissolved oxygen concentration. It showed a linearity of $0.5 \%$ full scale at constant temperature and could be operated over the temperature range $0^{\circ} \mathrm{C}$ to $90^{\circ} \mathrm{C}$.
(9) Recorder

The output of the oxygen analyser was recorded on a Sargent Model SRL Recorder.
(10) Manometer

A mercury manometer was used to indicate the pressure at the air inlet.
(11) Thermocouples and Potentiometer

All temperature measurements were made with pre-calibrated copperconstantan thermocouples and a Leeds and Northrup Co. No. 8657-C Double Range Potentiometer. The calibration curve for the thermocouples is shown in Appendix II.
(12) Variable flow meter

A size number 5, RGI spherical float flow meter was used. The calibration curve for air at standard conditions is shown in Appendix III.
(13) Thermoregulator and Relay

A Canlab-Magnetic Control Thermoregulator No. 81-635/2 was used. The temperature range was 0 to $50^{\circ} \mathrm{C}$, with subdivisions of $1^{\circ} \mathrm{C}$. The relay was a mercury plunger type 81-573/110, having a load rating of 3300 watts.
(14) Needle Valve

A high pressure gas needle valve was used to control the air flow rate accurately.
(15) Tachometer

A Jones Motroda Co. Model 4800, 3 dial, multiple range hand tachometer with stop button was used. A peripheral wheel normally used for measuring surface speeds was used for measuring the shaft speeds.
(16) Liquid Nitrogen

Canadian Liquid Air "L" grade nitrogen was used.

## II PROCEDURES

A. Unsteady Gassing Out Process

Water was added to the reactor to a depth of 2 tank diameters (15 inches), and was heated by the surrounding water bath to the desired temperature, within the range $25^{\circ} \mathrm{C}$ to $40^{\circ} \mathrm{C}$. The pH of the solution was adjusted with c.p. grade concentrated sulfuric acid or 18 Normal sodium hydroxide solution. The range covered was pH 1.0 to 12.5 .

Most of the tests were run in tap water. A few, however, were made in distilled water. Five agitation speeds (285, 380, 570, 760, and 950 rpm) were chosen. These were equivalent to ungassed Reynolds' numbers of $44,000,67,000,100,000,130,000$ and 170,000 in pure water at $70^{\circ} \mathrm{F}\left(21.1^{\circ} \mathrm{C}\right)$ respectively. The usually accepted Reynolds' number for the transition to turbulence in mixing tanks is around 1,000.

Prior to each test the dissolved oxygen was removed to a final concentration of approximately 0.5 ppm by the desorptive effect of rising nitrogen bubbles (43). The solution was then agitated for at least 5 minutes to remove any nitrogen bubbles in the solution.

Air preheated to the desired temperature during passage through the copper coil immersed in the water bath and saturated with water was injected through the nozzle (Figure 5). Unsaturated air was used in some of the tests in order to check the effect of saturation on the mass-transfer coefficient.

Dissolved oxygen was detemmined with the Beckman Oxygen Analyser. It was calibrated at the saturation value before each run. The signals from the anlyser were amplified and continuously recorded by the Sargent Recorder with respect to time. During the aeration interval, the agitator power consumption, the air flow rate, gas hold up, and the temperature of the solution were measured several times. Normally they were constant for a given run.

The over-all mass-transfer coefficients were calculated numerically according to equation (8) using an I.B.M. 7044 computer. The correlation work was also carried out with the same computer. The programs for these calculations are shown in Appendix IV and Appendix V.

The magnitude of aeration through the liquid surface should be measured. This should be done by measuring the oxygen accumulation when the air bubbles had the oxygen composition which was equivalent to the oxygen concentration in the solution. It was difficult to control the composition of the air bubbles so that this condition could be achieved, hence, we measured the oxygen accumulation while the air flow was turned off. It is realized that the exact values of surface aeration could not be obtained by using this method.


FIGURE 5. FLOWSHEET OF APPARATUS

## B. Sulfite-Oxidation Process

The apparatus used in the unsteady gassing out process was used in the sulfite-oxidation process. Distilled water was placed in the tank and the agitator was started. Approximately 1000 grams of c.p. grade sodium sulfite anhydrous powder were added to make the solution approximately 1.2 Normal with respect to the sulfite ion. After the sulfite powder had completely dissolved, predissolved c.p. cupric sulfate was added to give a $\mathrm{Cu}^{++}$ concentration of $10^{-3} \mathrm{M}$. The air was then turned on and a timer was started. The oxidation reaction was allowed to continue for 3-100 minutes, depending on the rate of oxidation. The oxidative reaction was exothermic especially at high agitation speeds. The addition of a cooling coil could possibly change the flow pattern in the reactor, so air without preheating was used. The temperature remained within $\pm 1^{\circ} \mathrm{C}$ of the desired value.

The rate of oxygen absorption was followed by the determination of the sulfite-ion concentration before and after each run. A 4.0 ml sample was taken directly from the reactor with a 10 ml syringe and was run immediately into an excess of freshly pipetted standard iodine solution (14). The tip of the syringe was held as closely as possible to the iodine standard solution surface, to prevent air oxidation of the samplefduring transfer. After at least a 10 minute wait, designed to ensure complete oxidation of sulfite to sulfate, the unreacted iodine was back-titrated with standard sodium thiosulfate solution to a starch indicator end point (44).

The over-all mass-transfer coefficients $K_{L}$ a were calculated according to equation (6) where:

$$
\begin{equation*}
K_{L} a=N A /\left(C^{*}\right) \tag{6}
\end{equation*}
$$

The logarithmic mean value of $C$ * was used.

## III RESULTS AND DISCUSSION

## A. Saturation Oxygen Concentrations

The modified Winkler Method (Appendix I) was used to measure the oxygen concentration of water in equilibrium with water-saturated air. However, this method could not be applied at low pH levels. Saturation values for 0. il N N sulfuric acid solutions were measured with a Beckman Oxygen Analyser. The values are compared in Table I with the experimental values calculated according to Eckenfelder's equation (45). It was concluded that pH had no effect on saturation values ( $C^{*}$ ) and so the calculated values were used in $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ calculations.
B. Effect of Unsaturated Air on $K_{L}$ a

Unsaturated air was used to check the effect of saturation on $K_{L}{ }^{a}$ at $30^{\circ} \mathrm{C}$ (Figure 6) and $35^{\circ} \mathrm{C}$ (Figure 7). The $\mathrm{K}_{\mathrm{L}}$ a values were plotted versus superficial gas velocities for two shaft speeds ( 950 rpm and 285 rpm ) on log-log paper. The data are in Appendix VII. At both temperatures $K_{L}{ }^{a}$ values for unsaturated air were found to fall on the same line as those for saturated air. This shows that the diffusional transfer of water vapor to the gas phase had an insignificant effect on $K_{L}$ a over the entire experimental range of gas flow rates ( $5.01 / \mathrm{min}$ to $52.41 / \mathrm{min}$, at $1 \mathrm{~atm} ., 21^{\circ} \mathrm{C}$ ).

TABLE I

Saturation Oxygen Concentration of Water and Acid Solution at Various Temperatures (ppm)

|  | $25{ }^{\circ} \mathrm{C}$ | $30{ }^{\circ} \mathrm{C}$ | $35^{\circ} \mathrm{C}$ | $40{ }^{\circ} \mathrm{C}$ |
| :--- | :--- | :--- | :--- | :--- |
| Calculated Value <br> (Eckenfelder eq (45) ) | 8.11 | 7.53 | 7.04 | 6.60 |
| Distilled Water <br> (by Winkler Method) | 8.10 | 7.50 | 7.03 | 6.60 |
| 0.1 N Sulfuric Acid <br> (by Oxygen Analyser) | 8.04 | 7.48 | 7.00 | 6.59 |




Hence, in later studies the air was used without making sure it was saturated. The same result was obtained by Chiang and Toor (4) in laminar liquid jet experiments.
C. Effect of Tap Water vs. Distilled Water on $K_{\text {E }}$ a

The effect of tap water versus distilled water on $K_{L}$ a was examined at $35^{\circ} \mathrm{C}$. When values of $\mathrm{K}_{\mathrm{L}}$ a were plotted against superficial gas velocities, using shaft speed as a parameter (Figure 8), the values of $\mathrm{K}_{\mathrm{L}}$ a for tap water were found to lie on the same line as those for distilled water. The data are shown in Appendix VII. Consequently tap water was used in all subsequent experiments.
D. Effect of Oxygen Concentration on $K_{L}$ a

To obtain a typical time versus oxygen concentration curve, such as is shown in Figure 9, the oxygen analyser was calibrated initially at the saturation value for the given conditions. Then the air was turned off, and the nitrogen turned on to strip the dissolved oxygen from the solution. After the nitrogen was shut off, the oxygen concentration continued to decrease slowly because of the time required for the nitrogen bubbles to escape from the reactor. When air was introduced into the reactor at the desired flow rate, the dissolved oxygen concentration increased with time (Figure 9). Table II presents the $\mathrm{K}_{\mathrm{L}}$ a values calculated from Figure 9 according to equation (8). The relatively constant values of $\mathrm{K}_{\mathrm{L}}$ a indicate that $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ is almost independent of the oxygen concentration over the range studied. The experimental data are presented in Appendix VII.



FIGURE 9. TYPICAL TIME-CONCENTRATION CURVE $\left(40^{\circ} \mathrm{C}, 570 \mathrm{RPM}, A N D V_{s}=126 \mathrm{CM} / \mathrm{MIN}\right)$

Sample Calculation of $\mathrm{K}_{\mathrm{L}}$ a Based on Fig. 9

Temperature $=40^{\circ} \mathrm{C}$
Saturation Oxygen Concentration $C^{*}=6.60$
Shaft Speed $=570 \mathrm{rpm}$
Superficial Velocity $=127 \mathrm{~cm} / \mathrm{min}$

| TIME <br> (Min) | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Oxygen Concentration (ppm) | 1.78 | 3.40 | 4.55 | 5.27 | 5.75 |
| $\begin{aligned} & \text { Driving Force } \\ & \mathrm{C}^{*}-\mathrm{C} \\ & \text { (ppm) } \end{aligned}$ | 4.82 | 3.20 | 2.05 | 1.33 | 0.85 |
| $\begin{aligned} & K_{L} a \\ & (\text { Min })^{-1} \end{aligned}$ |  |  |  |  |  |

## E. Correlation of $\mathrm{K}_{\mathrm{L}}$ a with Operating Variables

One way to examine the rate of mass transfer in agitated vessels is to compare the overall mass-transfer coefficient, $K_{L} a$, to the impeller power input and superficial gas velocity. However, there is considerable variation between the results obtained by various investigators with regard to the correlation of $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ and the operating variables (8, $21,32,37,38$ ).

In this study the $K_{L}$ a values were determined by the gassing out technique at $\mathrm{pH} 1.0,2.0$ and 5.7 (natural pH of tap water) and at solution temperatures of $25,30,35$ and $40^{\circ} \mathrm{C}$. In addition at $35^{\circ} \mathrm{C}$, values were determined at $\mathrm{pH} 1.5,4.5,7.0,10.0,11.0$ and 12.5 . The raw data are in Appendix VII. Figure 10 obtained at $35^{\circ} \mathrm{C}$ is typical of the results and shows that pH has no effect on $\mathrm{K}_{\mathrm{L}}$ a values.

The data were then rearranged in the form $(H P / V)^{a} \cdot\left(V_{S}\right)^{b}$ using a least squares curve fitting method. The computer program is shown in Appendix $V$. The $K_{L}$ a values obtained at various $\mathrm{pH}^{\prime}$ s were plotted against $(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}\left(\mathrm{V}_{\mathrm{S}}\right)^{\mathrm{b}}$ for the temperatures $25,30,35$ and $40^{\circ} \mathrm{C}$ (Figures 11-14). The " $a$ " and " $b$ " values calculated at different temperatures are as follows:

$$
\begin{align*}
& \left(\mathrm{K}_{\mathrm{L}} \mathrm{a}\right)_{25^{\circ} \mathrm{C}}=(7.5 \pm 0.06)(\mathrm{HP} / \mathrm{V})^{0.32} \pm 0.02\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.46} \pm 0.04 \\
& \left(\mathrm{~K}_{\mathrm{L}} \mathrm{a}\right)_{30^{\circ} \mathrm{C}}=(9.3 \pm 0.03)(\mathrm{HP} / \mathrm{V})^{0.33} \pm 0.02\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.46} \pm 0.03 \\
& \left(\mathrm{~K}_{\mathrm{L}} \mathrm{a}\right)_{35^{\circ} \mathrm{C}}=(8.6 \pm 0.05)(\mathrm{HP} / \mathrm{V})^{0.39} \pm 0.01\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.46} \pm 0.02 \\
& \left(\mathrm{~K}_{\mathrm{L}} \mathrm{a}\right)_{40^{\circ} \mathrm{C}}=(8.8 \pm 0.04)(\mathrm{HP} / \mathrm{V})^{0.40} \pm 0.01\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.50} \pm 0.02 \tag{40}
\end{align*}
$$

These confidence limite are for the $95 \%$ level. The computer program for these calculations is shown in Appendix 5-5.

In view of these confidence limits, one could say that the exponent on the gas superficial velocity is 0.5 . Since according to


FIGUFE 10. EFFECT OF PH ON Kla AT $35^{\circ} \mathrm{C}$


FIGURE I I. CORRELATION BETWEEN MASS TRANSFER AND POWER INPUT PER UNIT VOLUME OF UNGASSED LIQUID HP/V, AND SUPERFICIAL GAS VELOCITY $V$ s.


FIGURE 12. CORRELATION BETWEEN MASS TRANSFER COEFFICIENT Kl a AND POWER INPUT PER UNIT VOLUME OF LIQUID HPN, AND SUPERFICIAL GAS VELOCITY $V$ s .


FIGURE 13. CORRELATION BETWEEN MASS TRANSFER COEFFICIENT Kla AND POWER INPUT PER UNIT VOLUME OF LQUID HPIV, AND SUPERFICIL GAS VËLOCITY $v s$.


FIGURE 14. CORRELATION BETWEEN MASS TRANSFER COEFFICIENT Kla AND POWER INPUT PER UNIT VOLUME OF LIQUID HP/V, AND SUPERFICIAL GAS VELOCITY Vs.

Calderbank (38), the value of $K_{L}$ is independent of bubble size and rising velocity, but depends only on the physical properties of the system, any increase in $K_{L}$ a must be contributed only by an increase in interfacial area of the gas bubbles per unit volume of the liquid, $a$, hence,

$$
a \quad \alpha\left(V_{s}\right)^{0.50}
$$

which agrees with Calderbank's result (38). According to his light transmission experiments, the value of a in a stirred vessel varies with $\mathrm{V}_{\mathrm{S}}$ in the same way. It should be noted that precise comparison with other workers' results is made difficult by differences in the geometry of the studied tank systems.

The value of $\mathrm{K}_{\mathrm{L}}$ a increases with increasing temperature which is contrary to the conclusions reported by Robinson and Engel (19) and Yoshida et al (32). However, $0^{\prime}$ Connor suggests that according to equation (24), the ratio of $K_{L}$ at different temperatures is dependent on the temperature and the viscosity of the liquid, for example, the ratio of $\mathrm{K}_{\mathrm{L}}$ at $40^{\circ} \mathrm{C}$ to that at $25^{\circ} \mathrm{C}$ for pure water is:

$$
\begin{aligned}
\frac{\left(\mathrm{K}_{\mathrm{L}} \mathrm{a}\right) 40^{\circ} \mathrm{C}}{\left(\mathrm{~K}_{\mathrm{L}} \mathrm{a}\right) 25^{\circ} \mathrm{C}} & =\sqrt{\frac{\mathrm{T}_{40{ }^{\circ} \mathrm{C} \quad \mu_{25^{\circ} \mathrm{C}}}^{\mathrm{T}_{25^{\circ} \mathrm{C}}{ }^{4} 40^{\circ} \mathrm{C}}}{}} \\
& =\sqrt{\frac{313 \times 0.8937}{298 \times 0.6560}} \\
& =1.20
\end{aligned}
$$

The ratio is a constant for a given pair of temperatures. However, in my study the ratio of $\mathrm{K}_{\mathrm{L}}$ a is dependent on the power input. The ratio is not a constant for a given pair of temperatures.

$$
\frac{\left(\mathrm{K}_{\mathrm{L}} \mathrm{a}\right) 40^{\circ} \mathrm{C}}{\left(\mathrm{~K}_{\mathrm{L}} \mathrm{a}\right) 25^{\circ} \mathrm{C}}=1.2(\mathrm{HP} / \mathrm{V})^{0.08}
$$

## F. Sulfite-Oxygen Reaction Mechanism

The data obtained from the sulfite-oxidation experiments are shown in Appendix VII and plotted in Figures 15 to 18 . The resulting straight lines in these plots indicate that the copper-catalyzed sulfiteoxidation reaction is zero order with respect to sulfite concentration in all cases (shaft speeds of 280,570 and 950 rpm , and sulfite concentrations ranging from 0.06 to 1.30 N ). Hence, the diffusion rate of sulfite ions is not the rate limiting step. Therefore, this is not the case of infinitely fast reaction. This agrees with the results of Cooper (8) and Westerterp (15).

## G. Sulfite-Oxygen Absorption Mechanism

According to the data presented in Figure 19 - 21, the relationship between $K_{L}$ and superficial gas velocity $\mathrm{V}_{\mathrm{S}}$, as determined by the sulfite-oxidation process is:
$K_{L} a \quad \alpha \quad\left(V_{S}\right)^{0.50}$
The $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ values determined by the sulfite-oxidation process and by purely physical absorption are compared at different agitation speeds, in Figures 19 to 21. The data are given in Appendices VII-C and VIII.

According to Figures 19 to 21 the average ratios of $\mathrm{K}_{\mathrm{L}}$ a for the sulfite-oxidation process to $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ for pure water are: 9.0 at an agitation speed of $950 \mathrm{rpm}, 5.0$ at an agitation speed of $570 \mathrm{rpm}, 2.5$ at an agitation speed of 275 rpm . This was plotted on a logarithmic paper and shown in Figure 22. The resulting straight line has a slope of nearly 1.0. The more experiments are needed to confirm this.


FIG 15. TIME-CONCENTRATION CURVE FOR COPPER
CATALYZED SULFTE-OXYGEN REACTION AT $35^{\circ} \mathrm{C}(285 \mathrm{RPM})$.


FIG I6. TIME-CONCENTRATTON CURVE FOR COPPER
CATALYZED SULFITE-OXYGEN REACTION AT $35^{\circ} \mathrm{C}$ (570 RPM)


FIGIT. TIME-CONCENTRATION CURVE FOR COPPER CATALYZED SULFITE-OXYGEN. REACTION AT $35^{\circ} \mathrm{C}$ ( 950 R PM )


FIG I8. TIME-CONCENTRATION CURVE FOR COPPER CATALYZED SULFITE-OXYGEN REACTION AT $35^{\circ} \mathrm{C}$ ( 950 RPM)




FIGURE 2I. COMPARISON OF Kla $\mathbb{N}$ SULFITE OXIDATION PROCESS AND UNSTEADY GASSING OUT PROCESS ( $35^{\circ} \mathrm{C}, 285 \mathrm{RPM}$ )


FIGURE 22 THE PLOT OF AGITATION SPÉED VERSUS AVERAGE RATIO OF Kl a FOR THE SULFTE OXIDATION PROCESS TO K $a$ FOR PURE WATER AT $35^{\circ} \mathrm{C}$

There is little agreement among those investigators (21,22) who have tried to compare $K_{L}$ a values from sulfite-oxidation experiments with those obtained from real fermentations. As based on film theory, $\mathrm{K}_{\mathrm{L}} \mathrm{a}$ in a reaction system is dependent on film thickness, diffusivity and reaction rate constant. The fermentation broths generally differ greatly from sulfite solutions in physical and chemical properties. Physical properties, such as ionic strength, surface tension, and viscosity may affect the value of 'a' as well as $K_{L}$. The differences in these physical properties between fermentation broths and sulfite solutions can be minimized by using a very dilute solution, but this has no effect on chemical properties.

Since reaction rate constants vary from one reaction system to another, different $K_{L}$ 's from different reaction systems are expected. Hence, if the reaction rate constants are different, the comparison of $K_{L}$ between the two different systems is of little value. Furthermore, there are great differences between the diffusional processes involved in these two systems. In sulfite solution, oxygen passes from the gas through the interface into the liquid film. Oxygen utilization takes place in this film. In a suspension of microorganisms, the site of oxygen utilization is intimately associated with discrete cell units which are physically localized and relatively remote from the interface. So the best way of comparing the performance of different fermentation equipment is to use an actual fermentation system. H. Oxygen Supply

In order to supply the maximum oxygen uptake rate of $756 \mathrm{mg} / 1 / \mathrm{hr}$ (3) required by T. ferrooxidans when oxidizing chalcopyrite, the value of
$K_{L}$ a should be greater than $756 /(7.0-0) \mathrm{hr}^{-1}$ or $108 \mathrm{hr}^{-1}$ at $35^{\circ} \mathrm{C}$ (in this case, the oxygen concentration in the fermentation tank is assumed to be zero). This value of $\mathrm{K}_{\mathrm{L}}$ a for the case of pure physical absorption, is:

$$
\left(\mathrm{K}_{\mathrm{L}} \mathrm{a}\right) 35^{\circ} \mathrm{C}=8.6(\mathrm{HP} / \mathrm{V})^{0.39}\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.48}
$$

Therefore ( $\mathrm{HP} / \mathrm{V}$ ) ${ }^{0.39}\left(\mathrm{~V}_{\mathrm{s}}\right)^{0.48}$ should be greater than $108 / 8.6$ or 12.5 . This is easily achieved, for example, when $\mathrm{HP} / \mathrm{V}=10$ horsepower/ 1000 gallons of liquid, and $\mathrm{V}_{\mathrm{s}}=100 \mathrm{ft} / \mathrm{hr}$, the value of $\mathrm{K}_{\mathrm{L}}$ a will be $190 \mathrm{hr}^{-1}$, which is much greater than $108 \mathrm{hr}^{-1}$.

If oxygen supply is the rate limiting factor in bacterial growth during biological leaching of chalcopyrite, then, the physical properties of the biological suspension may limit the rate of oxygen absorption.

## I. Power Requirements in a Gassed System

Plots of $\mathrm{Pg} /$ Po versus $\mathrm{Q} /\left(\mathrm{ND}_{\mathrm{I}}{ }^{3}\right.$ ) based on the present data (Appendix VII) are shown in Figures 23. - 24. The results are not as simple as those shown by Ohyama (40), Moo-Young (41) and Aiba (42). The resulting curves are not only dependent on the shaft speed from 285 rpm to 950 rpm (Figure 22), but also dependent on the temperature of the liquid from $25^{\circ} \mathrm{C}$ to $40^{\circ} \mathrm{C}$ (Figure 23). Only at the highest shaft speed of 950 rpm does the effect of temperature seem insignificant. Further study of the power requirements in a gassed system would be of interest.

$\therefore \quad \because \quad-09-$

FIGURE 23. PONER CONSUMPTION VERSUS AERATION NUMBER. ( $35^{\circ} \mathrm{C}$ )

(1) The values of $\mathrm{K}_{\mathrm{L}}$ a were unaffected by solution pH over the range 1.0 to 12.5 . The use of unsaturated air or tap water also had no effect on $\mathrm{K}_{\mathrm{L}} \mathrm{A}$.
(2) The values of $\mathrm{K}_{\mathrm{L}}$ a obtained by the unsteady gassing out process were correlated as a form of $\mathrm{C} \cdot(\mathrm{HP} / \mathrm{V})^{\mathrm{a}} \cdot\left(\mathrm{V}_{\mathrm{S}}\right)^{\mathrm{b}}$, at $35^{\circ} \mathrm{C}$ for example:

$$
\left(\mathrm{K}_{\mathrm{L}} \mathrm{a}\right)_{35^{\circ} \mathrm{C}}=8.6(\mathrm{HP} / \mathrm{V})^{0.39}\left(\mathrm{~V}_{\mathrm{S}}\right)^{0.48}
$$

The value increased with increasing temperature of the solution.
(3) The copper-catalyzed sulfite-oxidation reaction was found to be zero order with respect to unreacted sulfite concentration. The values of $K_{L} \mathrm{a}$ from this technique were found to be proportional to $\left(\mathrm{V}_{\mathrm{S}}\right)^{0.50}$. When combined with the data obtained by the unsteady gassing out process, it was concluded that the interfacial area of the bubbles per unit volume of liquid 'a' was proportional to $\left(V_{S}\right)^{0.50}$.
(4) The oxygen demand of T. ferrooxidans oxidizing chalcopyrite would appear to be easily satisfied but further study on the rate of oxygen absorption during the biological fermentation is necessary to confirm this.
(5) Plots of $\mathrm{Pg} / \mathrm{Po}$ versus $\mathrm{Q} /\left(\mathrm{ND}_{\mathrm{I}}{ }^{3}\right)$ were not as straightforward as shown by other investigators. The resulting curves were dependent on the temperature of the liquid as well as the shaft speed of the impeller.

There are many problems to be solved both in the theory of oxygen transfer and in the application of the theory to tanks containing thousands of gallons of bacterial suspension.

If the rate of oxygen transfer is a rate limiting step in the rate of metabolism, a further study including the effects of ore particles, cell bodies and other nutrients on oxygen transfer rate is necessary.

Instead of using chemical systems, use of biological systems to study this type of mass transfer problem has certain advantages. Although the chemical systems are less sensitive to changes in physical and chemical properties the direct application of the data from chemical systems to the biological systems is extremely difficult. With biological systems, realistic values for the mass transfer rates can be obtained, even if thereaction and absorption mechanisms are unknown. The biological system is the most reliable method for evaluating the performance of fermentors.

The coefficient $K_{L}$ a is known to be dependent on the power input and superficial gas velocity. In most cases high superficial gas velocities are desired because it is more economical to increase the superficial gas velocity than to increase the agitator power imput. However, a minimum power input is necessary in order to assure the suspension and even distribution of ore particles and cell bodies. This is a very important factor when considering the economic value of a biological leaching process.

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## APPENDIX I

ALSTERBERG (AZIDE) MODIFICATION OF WINKLER METHOD (46)

## A. Reagents

(1) Manganous Sulfate Solution Dissolve $480 \mathrm{~g} \mathrm{MnSO}_{4} \cdot 4 \mathrm{H}_{2} \mathrm{O}, 400 \mathrm{~g} \mathrm{MnSO}_{4} \cdot 2 \mathrm{H}_{2} \mathrm{O}$, or 364 g $\mathrm{MnSO}_{4} \cdot \mathrm{H}_{2} \mathrm{O}$ in distilled water, filter, and dilute to 1 liter. When uncertainty exists regarding the water of crystallization, a solution of equivalent strength may be obtained by adjusting the specific gravity of the solution to a value of 1.270 at $20^{\circ} \mathrm{C}$. The manganous sulfate solution should liberate not more than a trace of iodine when added to an acidified solution of potassium iodide.
(2) A1kali-Iodide-Azide Reagent

Dissolve 500 g NaOH (or 700 g KOH ) and 135 g NaI (or 150 g KI ) in distilled water and dilute to 1 liter. To this solution add $10 \mathrm{~g} \mathrm{NaN}_{3}$ dissolved in 40 ml distilled water. Potassium and sodium salts may be used interchangeably. This reagent should not give a color with starch solution when dilute and acidified.
(3) Sulfuric Acid, Concentrated The strength of this acid is about 36 N . Hence, 1 ml is equivalent to about 3 ml of the alkali-iodide-azide reagent.
(4) Starch Solution

Prepare an emulsion of $5-6 \mathrm{~g}$ potato, arrowroot, or soluble starch in a mortar or beaker with a small quantity of distilled water. Pour this emulsion into 1 liter of boiling water, allow to boil a few minutes, and let settle overnight. Use the clear supernatant. This solution may be preserved with 1.25 g
salicylic acid per liter or by the addition of a few drops of toluene.
(5) Standard Sodium Thiosulfate Solution, 0.025 N Harleco Volumetric Concentrate Ampul was used. Hartman-Leddon Co. production.

Procedure
(1) To the sample, as collected in a 250 - to $300-\mathrm{ml}$ bottle, add 2 ml $\mathrm{MnSO}_{4}$ solution followed by 2 ml alkali-iodide-azide reagent, well below the surface of the liquid; stopper with care to exclude air bubbles and mix by inverting the bottle several times. When the precipitate settles, leaving a clear supernatant above the managanese hydroxide floc, shake again. When settling has produced at least 100 ml clear supernatant, carefully remove the stopper and immediately add 2.0 ml concentrated $\mathrm{H}_{2} \mathrm{SO}_{4}$ by allowing the acid to run down the neck of the bottle, restopper, and mix by gentle inversion until dissolution is complete. The iodine should be uniformly distributed throughout the bottle before decanting the amount needed for titration. This should correspond to 200 ml of the original sample after correction for the loss of sample by displacement with the reagents has been made. Thus, when a total of 4 ml ( 2 ml each) of the manganous sulfate and alkali-iodide-azide reagents is added to a $300-\mathrm{ml}$ bottle, the volume taken for titration should be

$$
200 \times \frac{300}{300-4}=203 \mathrm{~m} 1
$$

(2) Titrate with 0.025 N thiosulfate to a pale straw color. Add 1-2 ml freshly prepared starch solution and continue the titration to the first disappearance of the blue color. If the end point is overrun, the sample may be back-titrated with 0.025 N biniodate, which is added dropwise, or by an additional measured volume of sample. Correction for the amount of biniodate or sample should be made. Subsequent recolorations due to the catalytic effect of nitrite or to traces of ferric salts which have not been complexed with fluoride should be disregarded.



APPENDIX I I CALIBRATION CHART OF RGI FLOMMETER ( 1 ATM, $70^{\circ} \mathrm{F}$ )

COMPUTER PROGRAM FOR CALCULATION OF UNSTEADY GASSING OUT PROCESS




```
C
    DIMENSION Y(3,3), V(3)
    REAL PH,TEMP,RPM,POW,HOLD,KLA,SUPVEL
2000 DO 10 I I 1,3
    DO 10 J=1,3
10 Y(I,J)=0.0
1000 READ 20, PH,TEMP,RPM,POW,HOLD,KLA,SUPVEL
    RPM=RPM*1.9/0.5
    PHOLD=HOLD/15.0*100.0
20 FORMAT(7F10.0)
C
C POWER INPUT HORSEPOWER
C
    HP=5.0*POW*RPM/63025.0
C
C HP/1000.0 GALLON OF LIQUID
c VOLIME OF LOQUID IN (CM)**3, (FT)**3, U.S. GALLON
C
    AREA =(7.5*2.54/2.0)** 2*3.1416
    VCM=(7.5*2.54/2.0)**2*3.1416*15.0*2.54
    VFT=VCM/28316.0
    VGAL=VFT*7.481
C
    AA=HP/VGAL*1000.0
    BB=SUPVEL/30.48*60.0
    KLA=KLA*60.0
    IFITEMP.EQ.25.01 GO TO 52
    IF (TEMP.EQ. 30.0) GO TO 53
    IF (TEMP.EQ. 35.0) GO TO 54
    A =0.4011
    B=0.4974
    GO TO 51
52 A =0.3199
    B=0.4621
    GO TO 51
53 A=0.3286
    B=0.4562
    GO TO 51
54 A=0.3872
    B=0.4777
51. AAA=AA**A
    BBB=BB**B
```



SOURCE STATEMENT
\$IBFTC DATA
SUBROUTINE DAT ( $X, A V, P R O D, N R E A D, N R O W, N V A R, X M I N, X M A X)$
DIMENSION $X(70), A V(70), P R O D(70,70), X M I N(70), X M A X(70)$
DO $5 \mathrm{~K}=1$, NROW
READ $(5,4)(X(I), I=1$, NREAD $)$
4 FORMAT (3F10.0)
$X(1)=\operatorname{ALOG}(X(1))$
$X(2)=\operatorname{ALOG}(X(2))$
$X(3)=A L D G(X(3))$
C X=VARIABLES
C TRANSFORMATIONS ENTERED HERE
IF (K.NE.1) GO TO 3
C FIND MINIMUM AND MAXIMUM VALUES
DO $2 \mathrm{I}=1$, NVAR
XMIN(I) $=X(I)$
$X \operatorname{MAX}(I)=X(I)$
2 DO $1 \quad I=1$, NVAR
IF (X(I).LT.XMIN(I)) XMIN(I) $=X(I)$
IF (X(I).GT.XMAX(I)) XMAX(I)=X(I)
1 CONTINUE
C CALCULATE SUMS (AV) AND PRODUCTS (PROD)
DO $5 \mathrm{I}=1$, NVAR
$\operatorname{AV}(I)=\operatorname{AV}(I)+X(I)$
DO $6 \mathrm{~J}=\mathrm{I}, \mathrm{NVAR}$
$\operatorname{PROD}(I, J)=\operatorname{PROD}(I, J)+X(I) * X(J)$
$6 \quad \operatorname{PROD}(J, I)=\operatorname{PROD}(I, J)$
5 CONTINUE
RETURN
END
jES FOR ABOVE ASSEMBLY
. 7 SEC

COMPUTER PROGRAM OF SULFITE OXIDATION •PROCESS

SUPVEL $=B B$
\& PRINT 30, RPM, SUPVEL, AA
30 FORMAT(1X, 3F20.8)
CONCENTRATION OF SULFITE IN THE SOLUTION AT T(I)
ANORMI $=($ CCI 11$)-$ CCNA (1) $) * 0.2 /$ SAMP
$\mathrm{NN}=\mathrm{N}-1$
$\operatorname{SUM}=0.0$
DO $40 \quad \mathrm{I}=1, \mathrm{NN}$
c.
CONCENTRATION OF SULFITE IN THE SOLUTION AT T(2)
ANORM2 $=($ CCI $(I+1)-$ CCNA $(I+1)) * 0.2 /$ SAMP
$D T=T(1+1)-T(1)$
$\dot{C}$
C SATURATION GXYGEN CONCENTRATIÓN CSIN̈=7.0394

- O OXYGEN ABSORBED LITERS/MIN
OXYABS $=($ ANORMI-ANORM2 $) / 2 . * 22.4 * 10.86 / 0 T$
C
C. AIR INLET LITERS/MIN
AIRIN=SUPVEL*ARE/(30.48)**2/60.*28.32*273./308.
10
C. OXYGEN INLET LITERS/MIN OXYIN=AIRIN*0.21
C
C COMPOSITION OF OXYGEN IN OUTLET PERCENT
OUTLET=(OXYIN-OXYABS)/(AIRIN-OXYABS)
C OXYGEN CONCEN. IN EQUL. WITH OUTLET AIR CSOUT=CSIN*OUTLET
log mean value of saturation oxygen concen. CS = (CSIN-CSQUT)/2.303/ALOG(CSIN/CSOUT)
KLA $=($ ANORM1-ANORM2 $) * 16.0 * 1000.0 . . \quad / D T / C S$
$K L A=K L A * 60$.
PRINT50, KLA; OUTLET
50 FORMAT(1X,2F20.8)
40 CONTINUE
* AVKLA=SUM/FLOAT(NN)
PRINT 60, AVKLA

60. FORMAT (//1X,F20.8//)
C
C
$K L A=A V K L A * 60.0$
$Y Y=A L O G 10(K L A)$
$A A=A L O G 10(A A)$
$B B=A L O G 10(B B)$


## UNSTEADY GASSING OUT PROCESS

(A) Temperature $25^{\circ} \mathrm{C}$

$$
\begin{aligned}
& c=7.46 \\
& a=0.32
\end{aligned}
$$

pH value 1.0
$K_{L} a=c(H P / V)^{a}(V s)^{b}$

| Agitation speed rpm | Power Input HP/1000 Gals. | ```Superficial Velocity ft/hr``` | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{b} \end{aligned}$ | P/Po | $\begin{array}{ll} \mathrm{Q} / \mathrm{ND}_{\mathrm{T}}^{3} \\ \mathrm{x} & 10^{2} \end{array}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 0.000 | 0.300 | 0.000 | 1.000 | 0.000 |
| 285 | 1.024 | 35.610 | 35.340 | 5.252 | 0.867 | 0.345 |
| 285 | 0.709 | 67.618 | 49.440 | 6.280 | 0.600 | 0.655 |
| 285 | 0.630 | 141.398 | 60.540 | 8.504 | 0.533 | 1.370 |
| 285 | 0.552 | 262.697 | 70.320 | 10.849 | 0.467 | 2.545 |
| 285 | 0.552 | 362.815 | 78.120 | 12.595 | 0.467 | 3.576 |
| 380 | 3.152 | 0.000 | 0.480 | 0.000 | 1.000 | 0.000 |
| 380 | 2.837 | 36.024 | 53.160 | 7.314 | 0.900 | 0.262 |
| 380 | 2.102 | 67.618 | 78.720 | 8.889 | 0.667 | 0.491 |
| 380 | 1.576 | 141.398 | 92.280 | 11.401 | 0.500 | 1.027 |
| 380 | 1.471 | 233.622 | 95.220 | 14.064 | 0.467 | 1.697 |
| 380 | 1.366 | 358.071 | 120.180 | 16.731 | 0.433 | 2.604 |
| 570 | 11.033 | 0.000 | 1.080 | 0.000 | 1.000 | 0.000 |
| 570 | 10.245 | 35.886 | 86.280 | 11.010 | 0.929 | 0.174 |
| 570 | 8.826 | 67.618 | 126.600 | 14.068 | 0.800 | 0.328 |
| 570 | 5.989 | 141.398 | 149.520 | 17.474 | 0.543 | 0.685 |
| 570 | 5.359 | 235.000 | 163.740 | 21.326 | 0.486 | 1.139 |
| 570 | 5.044 | 359.016 | 178.800 | 25.441: | 0.457 | 1.740 |
| 760 | 25.218 | 0.000 | 1.080 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 35.748 | 111.780 | 14.661 | 1.000 | 0.132 |
| 760 | 21.015 | 67.618 | 162.000 | 18.567 | 0.833 | 0.246 |
| 760 | 14.711 | 140.925 | 180.660 | 23.258 | 0.583 | 0.516 |
| 760 | 13.030 | 230.846 | 198.420 | 28.103 | 0.517 | 0.840 |
| 760 | 12.609 | 353.346 | 206.400 | 33.856 | 0.500 | 1.284 |
| 950 | 52.538 | 0.000 | 2.400 | 0.000 | 1.000 | 0.000 |
| 950 | 49.912 | 35.886 | 105.180 | 18.272 | 0.950 | 0.104 |
| 950 | 42.031 | 67.382 | 201. 240 | 23.139 | 0.800 | 0.196 |
| 950 | 28.896 | 141.398 | 226.440 | 28.910 | 0.550 | 0.410 |
| 950 | 26.269 | 235.000 | 233.700 | 35.461 | 0.500 | 0.684 |
| 950 | 24.168 | 359.016 | 230.460 | 41.997 | 0.460 | 1.044 |

Temperature $25^{\circ} \mathrm{C}$
$c=7.46$
pH Value 2.0
$\mathrm{a}=0.32$
$\mathrm{K}_{\mathrm{L}} \mathrm{a}=\mathrm{c}(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}\left(\mathrm{V}_{\mathrm{S}}\right)^{\mathrm{b}}$
$b=0.46$

| Agitation <br> Speed rpm | Power Input HP/1000 Gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{Chr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{1}^{3} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 285 | 1.103 | 37.618 | 32.040 | 5.506 | 0.933 | 0.365 |
| 285 | 0.788 | 71.457 | 53.760 | 6.663 | 0.667 | 0.696 |
| 285 | 0.709 | 146.969 | 67.020 | 8.990 | 0.600 | 1.424 |
| 285 | 0.709 | 243.996 | 78.180 | 11.363 | 0.600 | 2.364 |
| 285 | 0.630 | 368.504 | 92.820 | 13.239 | 0.533 | 3.576 |
| 380 | 3.152 | 0.000 | 0.300 | 0.000 | 1.000 | 0.000 |
| 380 | 3.047 | 37.874 | 53.280 | 7.659 | 0.967 | 0.275 |
| 380 | 2.102 | 71.398 | 86.100 | 9.115 | 0.607 | 0.518 |
| 380 | 1.681 | 150.689 | 105.600 | 11.986 | 0.533 | 1.094 |
| 380 | 1.576 | 246.083 | 120.420 | 14.728 | 0.500 | 1.788 |
| 380 | 1.576 | 372.283 | 137.400 | 17.833 | 0.500 | 2.705 |
| 570 | 11.821 | 0.000 | 0.840 | 0.000 | 1.000 | 0.000 |
| 570 | 11.033 | 37.874 | 89.340 | 11.559 | 0.933 | 0.184 |
| 570 | 9.457 | 71.437 | 138.660 | 14.752 | 0.800 | 0.639 |
| 570 | 6.305 | 149.744 | 167.340 | 18.241 | 0.533 | 0.725 |
| 570 | 5.517 | 247.461 | 186.480 | 22.044 | 0.467 | 1.199 |
| 570 | 5.201 | 374.173 | 203.460 | 26.188 | 0.440 | 1.812 |
| 760 | 27.320 | 0.000 | 1.860 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 37.087 | 138.480 | 14.912 | 0.923 | 0.132 |
| 760 | 22.066 | 71.220 | 211.560 | 19.317 | 0.808 | 0.258 |
| 760 | 14.711 | 150.217 | 238.560 | 23.955 | 0.538 | 0.546 |
| 760 | 13.660 | 247.461 | 246.600 | 29.463 | 0.500 | 0.900 |
| 760 | 12.609 | 372.283 | 262.980 | 34.683 | 0.462 | 1.356 |
| 950 | 49.912 | 0.000 | 2.040 | 0.000 | 1.000 | 0.000 |
| 950 | 47.285 | 37.480 | 131.340 | 18.323 | 0.947 | 0.109 |
| 950 | 39.404 | 71.220 | 175.320 | 23.254 | 0.789 | 0.208 |
| 950 | 28.896 | 150.217 | 208.860 | 29.729 | 0.579 | 0.437 |
| 950 | 26.269 | 246.083 | 220.680 | 36.224 | 0.526 | 0.715 |
| 950 | 24.956 | 377.953 | 239.640 | 43.450 | 0.500 | 1.098 |

Temperature $25^{\circ} \mathrm{C}$
$c=7.46$
pH Value 5.7
$a=0.32$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$c=0.46$

| Agitation Speed rpm | Power Input HP/1000 Gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{b} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \times \quad 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 285 | 0.946 | 36.024 | 31.440 | 5.147 | 0.800 | 0.349 |
| 285 | 0.709 | 67.382 | 45.540 | 6.270 | 0.600 | 0.653 |
| 285 | 0.630 | 142.776 | 61.500 | 8.542 | 0.533 | 1.382 |
| 285 | 0.552 | 236.378 | 69.840 | 10.332 | 0.467 | 2.292 |
| 285 | 0.552 | 360.925 | 78.420 | 12.564 | 0.467 | 3.492 |
| 380 | 3.152 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 380 | 3.047 | 36.024 | 46.020 | 7.483 | 0.907 | 0.262 |
| 380 | 2.102 | 67.382 | 78.360 | 8.875 | 0.667 | 0.490 |
| 380 | 1.576 | 142.776 | 102.840 | 11.452 | 0.500 | 1.038 |
| 380 | 1.576 | 236.378 | 120.000 | 14.456 | 0.500 | 1.716 |
| 380 | 1.471 | 360.925 | 131.760 | 17.195 | 0.467 | 2.628 |
| 570 | 11.033 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 570 | 11.033 | 35.886 | 64.200 | 11.274 | 1.000 | 0.174 |
| 570 | 9.457 | 67.382 | 115.260 | 14.359 | 0.857 | 0.324 |
| 570 | 6.305 | 142.323 | 158.280 | 17.817 | 0.571 | 0.684 |
| 570 | 5.517 | 232.087 | 192.120 | 21.401 | 0.500 | 1.128 |
| 570 | 5.517 | 359.016 | 194.220 | 26.180 | 0.500 | 1.739 |
| 760 | 27.320 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 35.079 | 81.660 | 14.534 | 0.923 | 0.127 |
| 760 | 21.015 | 67.382 | 136.320 | 18,537 | 0.769 | 0.245 |
| 760 | 14.711 | 141.398 | 195.000 | 23.294 | 0.538 | 0.514 |
| 760 | 13.660 | 230.846 | 232.800 | 28.531 | 0.500 | 0.839 |
| 760 | 12.609 | 364.705 | 241.440 | 34.354 | 0.462 | 1.320 |
| 950 | 47.285 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| 950 | 47.285 | 35.610 | 90.480 | 17.895 | 0.947 | 0.103 |
| 950 | 39.404 | 67.382 | 150.360 | 22.666 | 0.833 | 0.196 |
| 950 | 28.896 | 141.850 | 215.580 | 28.952 | 0.611 | 0.412 |
| 950 | 24.956 | 234.311 | 273.540 | 34.837 | 0.528 | 0.680 |
| 950 | 22.329 | 363.760 | 310.860 | 41.196 | 0.472 | 1.057 |

(B) Temperature $30^{\circ} \mathrm{C}$
$c=9.27$
pH Value 1.0
$\mathrm{a}=0.33$
$K_{L} a=c(H P / V)^{a}(v s)^{b}$
$b=0.46$

| Agitation Speed rpm | Power Input HP/1000 Gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a}_{\text {hr }}{ }^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{b} \end{aligned}$ | P/Po | $\begin{array}{r} \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ \times \quad 10^{2} \end{array}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 0.000 | 1.740 | 0.000 | 1.000 | 0.000 |
| 285 | 1.103 | 36.024 | 36.060 | 5.298 | 0.933 | 0.348 |
| 285 | 0.788 | 67.382 | 51.600 | 6.312 | 0.667 | 0.653 |
| 285 | 0.630 | 236.378 | 77.580 | 10.399 | 0.533 | 2.292 |
| 285 | 0.630 | 360.925 | 94.860 | 12.614 | 0.533 | 3.492 |
| 380 | 3.152 | 0.000 | 0.060 | 0.000 | 1.000 | 0.000 |
| 380 | 2.627 | 36.024 | 60.420 | 7.046 | 0.827 | 0.262 |
| 380 | 2.102 | 67.618 | 85.680 | 8.727 | 0.688 | 0.492 |
| 380 | 1.576 | 141.850 | 105.540 | 11.133 | 0.503 | 1.031 |
| 380 | 1.576 | 233.622 | 122.640 | 13.978 | 0.503 | 1.692 |
| 380 | 1.576 | 360.925 | 142.980 | 17.046 | 0.503 | 2.622 |
| 570 | 10.245 | 0.000 | 0.540 | 0.000 | 1.000 | 0.000 |
| 570 | 10.245 | 35.886 | 97.200 | 11.000 | 1.000 | 0.173 |
| 570 | 8.669 | 67.382 | 141.840 | 13.880 | 0.846 | 0.326 |
| 570 | 6.305 | 142.323 | 177.060 | 17.583 | 0.615 | 0.690 |
| 570 | 5.517 | 232.224 | 193.020 | 21.040 | 0.538 | 1.124 |
| 570 | 5.517 | 359.016 | 211.560 | 25.666 | 0.538 | 1.740 |
| 760 | 25.218 | 0.000 | 0.300 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 35.079 | 121.140 | 14.637 | 1.000 | 0.127 |
| 760 | 19.965 | 67.382 | 183.480 | 18.258 | 0.792 | 0.245 |
| 760 | 13.660 | 141.398 | 217.200 | 22.602 | 0.542 | 0.514 |
| 760 | 13,660 | 230.846 | 250.560 | 28.266 | 0.542 | 0.839 |
| 760 | 12,609 | 364.705 | 265.320 | 33.919 | 0.500 | 1.320 |
| 950 | 49.912 | 0.000 | 2.640 | 0.000 | 1.000 | 0.000 |
| 950 | 47.285 | 35.610 | 175.440 | 18.119 | 0.947 | 0.103 |
| 950 | 39.404 | 67.382 | 244.560 | 22.828 | 0.789 | 0.196 |
| 950 | 28.896 | 141.850 | 292.260 | 28.953 | 0.579 | 0.408 |
| 950 | 25.218 | 234.311 | 303.960 | 34.810 | 0.505 | 0.682 |
| 950 | 23.642 | 363.760 | 318.720 | 41.652 | 0.474 | 1.057 |

Temperature $30^{\circ} \mathrm{C}$
$c=9.27$
pH Value 2.0
$a=0.33$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$b=0.46$

| Agitation Speed rpm | Power Input HP/1000 Gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \mathrm{x} \quad 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.576 | 0.000 | 0.420 | 0.000 | 1.000 | 0.000 |
| 285 | 1.576 | 37.618 | 37.920 | 6.076 | 1.000 | 0.365 |
| 285 | 1.340 | 71.220 | 55.380 | 7.707 | 0.850 | 0.690 |
| 285 | 0.946 | 149.744 | 69.960 | 9.648 | 0.600 | 1.452 |
| 285 | 0.630 | 244.843 | 88.920 | 10.568 | 0.400 | 2.376 |
| 285 | 0.552 | 373.228 | 104.460 | 12.259 | 0.350 | 3.612 |
| 380 | 4.203 | 0.000 | 0.600 | 0.000 | 1.000 | 0.000 |
| 380 | 3.993 | 37.736 | 58.500 | 8.259 | 0.953 | 0.275 |
| 380 | 3.362 | 71.220 | 94.140 | 10.428 | 0.800 | 0.517 |
| 380 | 2.837 | 148.819 | 110.160 | 13.803 | 0.677 | 1.081 |
| 380 | 2.732 | 246.083 | 142.680 | 17.149 | 0.650 | 1.788 |
| 380 | 2.627 | 373.228 | 158.880 | 20.472 | 0.626 | 2.712 |
| 570 | 11.821 | 0.000 | 1.200 | 0.000 | 1.000 | 0.000 |
| 570 | 11.821 | 37.480 | 102.660 | 11.761 | 1.000 | 0.181 |
| 570 | 9.142 | 71.220 | 154.680 | 14.486 | 0.773 | 0.344 |
| 570 | 6.777 | 150.689 | 182.280 | 18.481 | 0.573 | 0.730 |
| 570 | 6.305 | 245.394 | 197.580 | 22.544 | 0.533 | 1.189 |
| 570 | 5.832 | 371.319 | 215.760 | 26.544 | 0.493 | 1.799 |
| 760 | 26.269 | 0.000 | 1.860 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 37.618 | 139.618 | .15.111 | . 0.960 | 0.137 |
| 760 | 23.117 | 71.220 | 201. 540 | 19.649 | 0.880 | 0.259 |
| 760 | 15.762 | 150.217 | 239.340 | 24.353 | 0.600 | 0.546 |
| 760 | 14.711 | 246.772 | 263.400 | 29.857 | 0.560 | 0.896 |
| 760 | 12.609 | 370.374 | 274.980 | 34.159 | 0.480 | 1.344 |
| 950 | 52.538 | 0.000 | 3.420 | 0.000 | 1.000 | 0.000 |
| 950 | 49.912 | 37.480 | 167.760 | 18.880 | 0.950 | 0.109 |
| 950 | 42.031 | 71.220 | 246.540 | 23.915 | 0.800 | 0.208 |
| 950 | 28.896 | 150.217 | 282.900 | 29.720 | 0.550 | 0.437 |
| 950 | 26.269 | 247.461 | 306.720 | 36.170 | 0.500 | 0.720 |
| 950 | 23.642 | 369.429 | 315.840 | 41.947 | 0.450 | 1.074 |

                    \(c=9.27\)
    pH Value 5.7
$a=0.33$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$b=0.46$

| Agitation <br> Speed rpm | Power Iñput HP/1000 gals. | ```Superficial Velocity ft/hr``` | $\mathrm{K}_{\mathrm{L}} a \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{b} \end{aligned}$ | P/Po | $\begin{array}{ll} \hline \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ \mathrm{x} & 102 \end{array}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 32.972 | 37.740 | 4.966 | 1.000 | 0.000* |
| 285 | 0.867 | 59.724. | 60.660 | 6.164 | 0.846 | 0.578* |
| 285 | 0.709 | 117.697 | 74.340 | 7.864 | 0.692 | 1.140* |
| 285 | 0.630 | 178.917 | 85.440 | 9.159 | 0.615 | 1.728* |
| 285 | 0.630 | 252.087 | 101.880 | 10.709 | 0.615 | 2.448* |
| 285 | 1.103 | 37.736 | 35.280 | 5.412 | 1.000 | 0.000 |
| 285 | 0.867 | 71.220 | 58.440 | 6.680 | 0.786 | 0.690 |
| 285 | 0.709 | 150.217 | 73.860 | 8.790 | 0.643 | 1.452 |
| 285 | 0.709 | 246.083 | 84.540 | 11.010 | 0.643 | 2.388 |
| 285 | 0.709 | 371.319 | 103.260 | 13.283 | 0.643 | 3.598 |
| 380 | 2.732 | 37.874 | 59.700 | 7.302 | 1.000 | 0.275 |
| 380 | 2.207 | 71.220 | 92.280 | 9.080 | 0.808 | 0.517 |
| 380 | 1.681 | 151.142 | 114.900 | 11.705 | 0.615 | 1.098 |
| 380 | 1.576 | 246.772 | 142.020 | 14.332 | 0.577 | 1.788 |
| 380 | 1.576 | 375.118 | 167.520 | 17.349 | 0.577 | 2.725 |
| 570 | 11.003 | 37.736 | 109.500 | 11.533 | 1.000 | 0.182 |
| 570 | 9.457 | 71.220 | 172.620 | 14.648 | 0.857 | 0.345 |
| 570 | 6.620 | 150.689 | 201.780 | 18.339 | 0.600 | 0.730 |
| 570 | 5.989 | 248.150 | 236.280 | 22.280 | 0.543 | 1.200 |
| 570 | 5.517 | 376.063 | 263.760 | 26.215 | 0.500 | 1.824 |
| 760 | 25.218 | 37.480 | 145.380 | 15.086 | 1.000 | 0.136 |
| 760 | 22.066 | 70.965 | 227.760 | 19.319 | 0.875 | 0.258 |
| 760 | 15.762 | 150.217 | 284.940 | 24.353 | 0.625 | 0.546 |
| 760 | 13.660 | 247.461 | 316.800 | 29.176 | 0.542 | 0.899 |
| 760 | 12.609 | 376.063 | 349.740 | 34.397 | 0.500 | 1. 368 |
| 950 | 49.912 | .0:000 | 3.540 | 0.000 | 1.000 | 0.000* |
| 950 | 47.285 | 32.697 | 175.200 | 17.427 | 0.947 | $0.095 *$ |
| 950 | 42.031 | 59.232 | 265.320 | 21.986 | 0.842 | $0.172^{*}$ |
| 950 | 28.896 | 117.224 | 307.920 | 26.541 | 0.579 | $0.341 *$ |
| 950 | 26.269 | 178.917 | 349.680 | 31.195 | 0.526 | 0.520* |
| 950 | 24.956 | 251.969 | 403.140 | 35.860 | 0.500 | $0.732 *$ |
| 950 | 47.285 | 37.618 | 165.540 | 18.578 | 0.947 | 0.109 |
| 950 | 42.031 | 71.220 | 268.620 | 23.915 | 0.889 | 0.208 |
| 950 | 28.896 | 150.689 | 332.640 | 29.763 | 0.611 | 0.438 |
| 950 | 26.269 | 248.150 | 373.740 | 36.216 | 0.556 | 0.721 |
| 950 | 24.956 | 373.228 | 410.100 | 42.899 | 0.528 | 1.085 |

[^0](C) Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH Value 1.0
$\mathrm{a}=0.39$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$b=0.48$

| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Velocity ft/hr | $K_{L} a h r l^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \mathrm{x} \quad 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 37.618 | 40.440 | 5.710 | 1.000 | 0.365 |
| 285 | 0.788 | 71.220 | 62.760 | 6.997 | 0.769 | 0.688 |
| 285 | 0.709 | 149.744 | 81.120 | 9.581 | 0.692 | 1.452 |
| 285 | 0.709 | 246.083 | 97.140 | 12.147 | 0.692 | 2.376 |
| 285 | 0.709 | 371.319 | 115.440 | 14.784 | 0.692 | 3.612 |
| 380 | 2.627 | 37.480 | 62.400 | 8.208 | 1.000 | 0.274 |
| 380 | 1.891 | 70.965 | 94.740 | 9.804 | 0.720 | 0.516 |
| 380 | 1.576 | 150.217 | 117.660 | 13.072 | 0.600 | 1.092 |
| 380 | 1.471 | 246.772 | 151.320 | 16.133 | 0.560 | 1.788 |
| 380 | 1.366 | 376.063 | 183.840 | 19.171 | 0.520 | 2.692 |
| 570 | 10.718 | 37.618 | 115.500 | 14.172 | 1.000 | 0.182 |
| 570 | 8.669 | 70.965 | 182.760 | 17.678 | 0.809 | 0.343 |
| 570 | 6.305 | 150.217 | 232.560 | 22.359 | 0.588 | 0.727 |
| 570 | 5.674 | 247.461 | 277.740 | 27.245 | 0.529 | 1.200 |
| 570 | 5.359 | 376.063 | 298.140 | 32.546 | 0.500 | 1.824 |
| 760 | 25.218 | 37.480 | 169.740 | 19,704 | 1.000 | 0.136 |
| 760 | 21.015 | 70.965 | 270.540 | 24.907 | 0.833 | 0.258 |
| 760 | 14.711 | 149.744 | 315.960 | 30.994 | 0.583 | 0.544 |
| 760 | 13.450 | 246.772 | 355.680 | 38.005 | 0.533 | 0.896 |
| 760 | 12.609 | 376.063 | 360.780 | 45.330 | 0.500 | 1.368 |
| 950 | 47.285 | 37.205 | 202.020 | 25.045 | 1.000 | 0.108 |
| 950 | 42.031 | 70.728 | 314.340 | 32.523 | 0.889 | 0.205 |
| 950 | 28.896 | 150.217 | 388.080 | 40.314 | 0.611 | 0.437 |
| 950 | 26.269 | 247.461 | 442.020 | 49.316 | 0.556 | 0.720 |
| 950 | 23.642 | 376.063 | 459.840 | 57,822 | 0.500 | 1.093 |

Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH value 1.5
$a=0.39$
$K_{L} a=c(H P / V)^{a}(v s)^{b}$
$b=0.48$

| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Velocity ft/hr | $\mathrm{K}_{\overline{\mathrm{L}}} \mathrm{a}^{\text {a }} \mathrm{hr} \overline{\mathbf{r}}^{-1}$ | $\begin{aligned} & (H P)^{a} \\ & (V s)^{b} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}^{3} \mathrm{I} \\ & \mathrm{x} \\ & \hline \end{aligned} 0^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.103 | 37.618 | 41.880 | 5.876 | 1.000 | 0.365 |
| 285 | 0.788 | 70.965 | 64.320 | 6.985 | 0.714 | 0.688 |
| 285 | 0.709 | 150.689 | 82.980 | 9.610 | 0.643 | 1.464 |
| 285 | 0.709 | 248.858 | 101.880 | 12.212 | 0.643 | 2.412 |
| 285 | 0.709 | 376.063 | 124.920 | 14.874 | 0.643 | 3.648 |
| 380 | 3.152 | 37.618 | 72.300 | 8.823 | 1.000 | 0.274 |
| 380 | 2.312 | 71.220 | 106.560 | 10.615 | 0.733 | 0.516 |
| 380 | 1.786 | 150.217 | 144.420 | 13.721 | 0.567 | 1.092 |
| 380 | 1.681 | 246.772 | 166.440 | 16.989 | 0.533 | 1.793 |
| 380 | 1.576 | 376.063 | 192.840 | 20.263 | 0.500 | 3.279 |
| 570 | 10.245 | 37.205 | 118.200 | 13.853 | 1.000 | 0.180 |
| 570 | 9.457 | 70.965 | 194.940 | 18.283 | 0.923 | 0.343 |
| 570 | 6.305 | 150.217 | 235.440 | 22.359 | 0.615 | 0.727 |
| 570 | 5.674 | 248.150 | 281.100 | 27.281 | 0.554 | 1.200 |
| 570 | 5.359 | 376.063 | 325.020 | 32.546 | 0.523 | 1.824 |
| 760 | 25.218 | 37.618 | 174.240 | 19.738 | 1.000 | 0.137 |
| 760 | 21.015 | 70.728 | 265.080 | 24.868 | 0.833 | 0.257 |
| 760 | 14.711 | 150.217 | 318.960 | 31.040 | 0.583 | 0.546 |
| 760 | 13.450 | 248.150 | 356.220 | 38.106 | 0.533 | 0.901 |
| 760 | 12.609 | 376.063 | 393.480 | 45.330 | 0.500 | 1.368 |
| 950 | 49.912 | 36.949 | 208.860 | 25.491 | 1.000 | 0.107 |
| 950 | 42.031 | 70.728 | 316.860 | 32.523 | 0.842 | 0.205 |
| 950 | 28.896 | 150.217 | 397.980 | 40.314 | 0.579 | 0.437 |
| 950 | 24.956 | 246.772 | 435.840 | 48.282 | 0.500 | 0.718 |
| 950 | 23.642 | 376.063 | 453.480 | 57.822 | 0.474 | 1.093 |

```
Temperature \(35^{\circ} \mathrm{C}\)
    \(c=8.58\)
pH value 2.0
    \(a=0.39\)
\(\mathrm{K}_{\mathrm{L}} \mathrm{a}=\mathrm{c}(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}(\mathrm{Vs})^{\mathrm{b}}\)
b \(=0.48\)
```

| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 0.000 | 0.420 | 0.000 | 1.000 | 0.000 |
| 285 | 1.024 | 37.618 | 39.060 | 5.710 | 0.867 | 0.365 |
| 285 | 0.788 | 70.965 | 61.620 | 6.985 | 0.667 | 0.688 |
| 285 | 0.709 | 149.744 | 78.180 | 9.581 | 0.600 | 1.452 |
| 285 | 0.709 | 244.705 | 100.740 | 12.114 | 0.600 | 2.376 |
| 285 | 0.630 | 368.484 | 105.160 | 14.074 | 0.533 | 3.576 |
| 380 | 3.047 | 0.000 | 0.720 | 0.000 | 1.000 | 0.000 |
| 380 | 2.837 | 37.618 | 64.440 | 8.471 | 0.931 | 0.274 |
| 380 | 2.102 | 71.220 | 94.800 | 10.230 | 0.689 | 0.517 |
| 380 | 1.576 | 149.291 | 122.760 | 13.033 | 0.517 | 1.085 |
| 380 | 1.576 | 247.461 | 140.280 | 16.592 | 0.517 | 1.798 |
| 380 | 1.471 | 370.374 | 174.000 | 19.586 | 0.483 | 2.688 |
| 570 | 10.245 | 37.205 | 114.960 | 13.853 | 0.929 | 0.180 |
| 570 | 9.457 | 70.965 | 170.760 | 18.283 | 0.857 | 0.343 |
| 570 | 6.305 | 150.689 | 200.760 | 22.392 | 0.571 | 0.730 |
| 570 | 5.674 | 247.461 | 220.440 | 27.245 | 0.514 | 1.200 |
| 570 | 5.359 | 373.228 | 243.360 | 32.429 | 0.486 | 1.812 |
| 760 | 25.218 | 0.000 | 2.460 | 0.000 | 1.000 | 0.000 |
| 760 | 26.269 | 37.343 | 152.940 | 19.983 | 1.000 | 0.136 |
| 760 | 23.117 | 70.728 | 220.380 | 25.803 | 0.917 | 0.257 |
| 760 | 14.711 | 148.819 | 250.620 | 30.902 | 0.583 | 0.649 |
| 760 | 13.660 | 246.772 | 274.020 | 38.234 | 0.542 | 0.896 |
| 760 | 12.609 | 373.228 | 303.540 | 45.167 | 0.500 | 1.356 |
| 950 | 52.538 | 0.000 | 4.620 | 0.000 | 1.000 | 0.000 |
| 950 | 49.912 | 37.343 | 178.680 | 25.620 | 0.950 | 0.109 |
| 950 | 42.031 | 70.728 | 266.640 | 32.523 | 0.800 | 0.205 |
| 950 | 28.896 | 150.217 | 298.320 | 40.314 | 0.550 | 0.537 |
| 950 | 26.269 | 247.461 | 326.220 | 49.316 | 0.500 | 0.719 |
| 950 | 23.642 | 373.228 | 331.740 | 57.614 | 0.450 | 1.085 |


| Temperature $35^{\circ} \mathrm{C}$ | $\mathrm{c}=8.58$ |
| :--- | :--- |
| pH value 4.5 | $\mathrm{a}=0.39$ |
| $\mathrm{~K}_{\mathrm{L}} \mathrm{a}=\mathrm{c}(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}(\mathrm{Vs})^{\mathrm{b}}$ | $\mathrm{b}=0.48$ |


| Agitation <br> Speed rpm | Power Input HP/1000 gals: | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \times \quad 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 38.012 | 41.460 | 5.738 | 1.000 | 0.368 |
| 285 | 0.709 | 71.693 | 61.920 | 6.739 | 0.692 | 0.695 |
| 285 | 0.630 | 152.992 | 77.700 | 9.248 | 0.615 | 1.490 |
| 285 | 0.630 | 248.858 | 98.940 | 11.667 | 0.615 | 2.412 |
| 285 | 0.630 | 376.063 | 102.720 | 14.211 | 0.615 | 3.648 |
| 380 | 2.627 | 38.012 | 60.720 | 8.263 | 1.000 | 0.272 |
| 380 | 1.891 | 71.693 | 91.740 | 9.852 | 0.720 | 0.516 |
| 380 | 1.576 | 152.067 | 119.400 | 13.148 | 0.600 | 1.092 |
| 380 | 1.471 | 250.925 | 146.520 | 16.262 | 0.560 | 1.793 |
| 380 | 1.471 | 375.118 | 162.060 | 19.706 | 0.520 | 2.732 |
| 570 | 11.033 | 37.874 | 116.940 | 14.378 | 1.000 | 0.184 |
| 570 | 9.457 | 71.693 | 184.200 | 18.373 | 0.857 | 0.347 |
| 570 | 6.305 | 152.067 | 226.500 | 22.490 | 0.571 | 0.737 |
| 570 | 5.832 | 250.236 | 260.760 | 27.683 | 0.529 | 1.212 |
| 570 | 5.517 | 377.953 | 295.320 | 32.992 | 0.500 | 1.830 |
| 760 | 23.117 | 71.457 | 245.880 | 25.929 | 1.000 | 0.259 |
| 760 | 15.131 | 152.067 | 295.860 | 31.565 | 0.655 | 0.552 |
| 760 | 13.660 | 250.925 | 355.500 | 38.540 | 0.591 | 0.912 |
| 760 | 12.609 | 379.843 | 356.820 | 45.547 | 0.545 | 1.380 |
| 950 | 49.912 | 37.736 | 187.800 | 25.749 | 1.000 | 0.110 |
| 950 | 39.404 | 71.457 | 306.000 | 31.876 | 0.789 | 0.208 |
| 950 | 28.896 | 148.898 | 358.620 | 40.144 | 0.579 | 0.433 |
| 950 | 26.269 | 257.874 | 437.880 | 50.297 | 0.526 | 0.750 |
| 950 | 24.693 | 377.008 | 467.100 | 58.875 | 0.495 | 1.096 |

Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH value 5.7 (Distilled Water)
$\mathrm{a}=0.39$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$\mathrm{b}=0.48$

| Agitation Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{A} h \mathrm{r}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND} \mathrm{D}_{\mathrm{I}} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 0.946 | 33.091 | 38.820 | 5.207 | 1.000 | 0.320* |
| 285 | 0.788 | 59.961 | 59.100 | 6.445 | 0.833 | 0.528* |
| 285 | 0.709 | 117.697 | 75.600 | 8.540 | 0.750 | 1.140* |
| 285 | 0.709 | 179.606 | 89.280 | 10.450 | 0.750 | 1.740* |
| 285 | 0.630 | 253.031 | 99.720 | 11.760 | 0.667 | 2.448* |
| 285 | 0.946 | 37.736 | 40.500 | 5.544 | 1.000 | 0.366 |
| 285 | 0.788 | 71.220 | 60.120 | 6.997 | 0.833 | 0.690 |
| 285 | 0.630 | 150.217 | 73.860 | 9.167 | 0.667 | 1.452 |
| 285 | 0.630 | 247.461 | 86.700 | 11.636 | 0.667 | 2.400 |
| 285 | 0.552 | 372.283 | 115.500 | 13.430 | 0.583 | 3.672 |
| 380 | 2.837 | 38.012 | 68.940 | 8.513 | 1.000 | 0.276 |
| 380 | 2.837 | 38.012 | 68.940 | 8.513 | 1.000 | 0.276 |
| 380 | 2.102 | 71.220 | 106.020 | 10.230 | 0.741 | 0.517 |
| 380 | 1.681 | 151.142 | 131.460 | 13.442 | 0.593 | 1.098 |
| 380 | 1.471 | 247.461 | 155.280 | 16.154 | 0.519 | 1.798 |
| 380 | 1.471 | 374.173 | 180.060 | 19.682 | 0.519 | 2.719 |
| 570 | 11.033 | 0.000 | 1.380 | 0.000 | 1.000 | 0.000 |
| 570 | 11.033 | 37.480 | 110.760 | 14.307 | 1.000 | 0.181 |
| 570 | 8.669 | 71.220 | 182.040 | 17.708 | 0.786 | 0.346 |
| 570 | 6.305 | 151.142 | 217.260 | 22.424 | 0.571 | 0.732 |
| 570 | 5.832 | 248.150 | 263.220 | 27.57.2 | 0.529 | 1.200 |
| 570 | 5.517 | 374.154 | 269.580 | 32.834 | 0.500 | 1.812 |
| 760 | 27.320 | 0.000 | 2.040 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 37.618 | 156.660 | 19.738 | 0.923 | 0.137 |
| 760 | 23.117 | 70.965 | 263.820 | 25.844 | 0.846 | 0.258 |
| 760 | 14.711 | 150.689 | 305.580 | 31.087 | 0.538 | 0.547 |
| 760 | 13.660 | 248.150 | 340.140 | 38.335 | 0.500 | 0.901 |
| 760 | 12.609 | 377.953 | 365.640 | 45.439 | 0.462 | 1.368 |
| 950 | 49.912 | 0.000 | 4.680 | 0.000 | 1.000 | 0.000* |
| 950 | 49.912 | 32.697 | 168.960 | 24.045 | 1.000 | 0.095* |
| 950 | 28.896 | 117.224 | 305.340 | 35.810 | 0.579 | 0.341* |
| 950 | 42.031 | 59.232 | 259.260 | 29.881 | 0.842 | 0.172* |
| 950 | 26.269 | 178.917 | 340.080 | 42.238 | 0.526 | 0.520* |
| 950 | 24.956 | 252.087 | 382.740 | 48.776 | 0.500 | 0.733* |
| 950 | 49.912 | 37.343 | 191.160 | 25.620 | 1.000 | 0.108 |
| 950 | 42.031 | 70.965 | 299.880 | 32.575 | 0.842 | 0.206 |
| 950 | 27.583 | 150.689 | 365.280 | 39.654 | 0.553 | 0.438 |
| 950 | 26.269 | 249.547 | 417.540 | 49.514 | 0.526 | 0.725 |
| 950 | 23.642 | 374.173 | 436.560 | 57.683 | 0.474 | 1.087 |

Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH value 10.0
$a=0.39$
$K_{L}{ }^{a}=c(H P / V)^{a}(V s)^{b}$
$\mathrm{b}=0.48$

| Agitation Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{ahr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{b} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND} \frac{3}{\mathrm{I}} \\ & \mathrm{x} \quad 102 \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 37.618 | 43.080 | 5.710 | 1.000 | 0.365 |
| 285 | 0.788 | 70.965 | 62.100 | 6.985 | 0.769 | 0.690 |
| 285 | 0.709 | 150.217 | 76.860 | 9.595 | 0.692 | 1.452 |
| 285 | 0.709 | 244.705 | 91.440 | 12.114 | 0.692 | 2.388 |
| 285 | 0.709 | 372.283 | 112.260 | 14.803 | 0.692 | 3.598 |
| 380 | 2.837 | 37.618 | 62.820 | 8.471 | 1.000 | 0.274 |
| 380 | 1.996 | 70.965 | 94.380 | 10.012 | 0.704 | 0.516 |
| 380 | 1.576 | 150.217 | 123.720 | 13.072 | 0.556 | 1.092 |
| 380 | 1.471 | 245.394 | 143.460 | 16.090 | 0.519 | 1.788 |
| 380 | 1.471 | 370.374 | 168.300 | 19.586 | 0.519 | 2.692 |
| 570 | 11.033 | 37.480 | 115.620 | 14.307 | 1.000 | 0.181 |
| 570 | 8.826 | 70.965 | 180.480 | 17.801 | 0.800 | 0.312 |
| 570 | 6.305 | $\therefore 149.744$ | 214.800 | 22.325 | 0.571 | 0.724 |
| 570 | 5.674 | 246.772 | 251.520 | 27.209 | 0.514 | 1.195 |
| 570 | 5.359 | 371.319 | 274.980 | 32.349 | 0.486 | 1.799 |
| 760 | 25.218 | 37.205 | 164.160 | 19.635 | 1.000 | 0.136 |
| 760 | 22.066 | 70.728 | 245.220 | 25.342 | 0.875 | 0.257 |
| 760 | 15.131 | 150.689 | 297.840 | 31.428 | 0.600 | 0.547 |
| 760 | 13.660 | 249.429 | 335.100 | 38.430 | 0.542 | 0.905 |
| 760 | 12.609 | 377.953 | 363.720 | 45.439 | 0.500 | 1.373 |
| 950 | 47.285 | 37.205 | 204.480 | 25.045 | 1.000 | 0.108 |
| 950 | 42.031 | 70.728 | 315.180 | 32.523 | 0.889 | 0.205 |
| 950 | 28.896 | 151.142 | 388.440 | 40.432 | 0.611 | 0.439 |
| 950 | 25.744 | 247.461 | 399.180 | 48.932 | 0.544 | 0.720 |
| 950 | 23.642 | 377.008 | 460.320 | 57.892 | 0.500 | 1.096 |

Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH value 11.0
$\mathrm{a}=0.39$
$K_{L}{ }^{a}=c(H P / V)^{a}(V s)^{b}$
$c=0.48$

| Agitation Speed rpm | Power Input HP/1000 gals. | Superficial Vēlocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{ahr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{VS})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND} \frac{3}{\mathrm{I}} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.103 | 37.618 | 39.720 | 5.876 | 1.000 | 0.365 |
| 285 | 0.788 | 70.965 | 61.500 | 6.985 | 0.714 | 0.688 |
| 285 | 0.709 | 149.744 | 80.640 | 9.581 | 0.643 | 1.452 |
| 285 | 0.709 | 244.705 | 93.420 | 12.114 | 0.643 | 2.376 |
| 285 | 0.709 | 371.319 | 113.280 | 14.784 | 0.643 | 3.600 |
| 380 | 2.837 | 37.480 | 60.660 | 8.456 | 1.000 | 0.272 |
| 380 | 2.312 | 70.965 | 98.700 | 10.596 | 0.815 | 0.515 |
| 380 | 1.576 | 149.744 | 120.480 | 13.052 | 0.556 | 1.088 |
| 380 | 1.471 | 248.150 | 145.020 | 16.176 | 0.519 | 1.804 |
| 380 | 1.471 | 377.008 | 167.040 | 19.753 | 0.519 | 2.738 |
| 570 | 11.033 | 37.343 | 105.660 | 14.281 | 1.000 | 0.181 |
| 570 | 8.669 | 70.965 | 170.040 | 17.678 | 0.786 | 0.343 |
| 570 | 5.674 | 149.744 | 202.980 | 21.433 | 0.514 | 0.725 |
| 570 | 5.359 | 246.772 | 223.260 | 26.613 | 0.486 | 1.195 |
| 570 | 5.044 | 375.118 | 260.280 | 31.753 | 0.457 | 1.817 |
| 760 | 25.218 | 37.343 | 147.540 | 19.669 | 1.000 | 0.136 |
| 760 | 21.015 | 70.728 | 226.080 | 24.868 | 0.833 | 0.257 |
| 760 | 14.711 | 150.217 | 277.500 | 31.040 | 0.583 | 0.546 |
| 760 | 13.660 | 246.083 | 306.180 | 38.183 | 0.542 | 0.894 |
| 760 | 12.609 | 376.063 | 330.780 | 45.330 | 0.500 | 1.368 |
| 950 | 47.285 | 37.343 | 170.760 | 25.090 | 1.000 | 0.109 |
| 950 | 39.404 | 70.965 | 260.100 | 31.771 | 0.833 | 0.206 |
| 950 | 27.583 | 150.197 | 294.360 | 39.592 | 0.583 | 0.437 |
| 950 | 25.744 | 248.150 | 344.220 | 48.997 | 0.544 | 0.721 |
| 950 | 23.642 | 374.173 | 352.500 | 57.683 | 0.500 | 1.087 |

Temperature $35^{\circ} \mathrm{C}$
$c=8.58$
pH value 12.5
$\mathrm{a}=0.39$
$K_{L} a=c(H P / V)^{a}(V s)^{b}$
$a=0.48$

| Agitation Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.182 | 37.343 | 43.740 | 6.014 | 1.000 | 0.361 |
| 285 | 0.867 | 70.728 | 67.500 | 7.237 | 0.733 | 0.685 |
| 285 | 0.788 | 149.291 | 81.780 | 9.965 | 0.667 | 1.452 |
| 285 | 0.709 | 243.996 | 90.360 | 12.097 | 0.600 | 2.364 |
| 285 | 0.709 | 374.173 | 126.960 | 14.839 | 0.600 | 3.624 |
| 380 | 2.627 | 37.480 | 70.680 | 8.208 | 1.000 | 0.272 |
| 380 | 2.102 | 70.728 | 113.460 | 10.196 | 0.800 | 0.514 |
| 380 | 1.681 | 149.744 | 131.100 | 13.382 | 0.640 | 1.088 |
| 380 | 1.576 | 245.394 | 155.880 | 16.525 | 0.600 | 1.788 |
| 380 | 1.471 | 374.173 | 179.040 | 19.682 | 0.560 | 2.719 |
| 570 | 10.245 | 37.343 | 125.040 | 13.878 | 1.000 | 0.181 |
| 570 | 8.669 | 70.728 | 186.660 | 17.649 | 0.846 | 0.343 |
| 570 | 5.989 | 149.744 | 220.500 | 21.886 | 0.585 | 0.725 |
| 570 | 5.517 | 246.083 | 263.580 | 26.878 | 0.538 | 1.192 |
| 570 | 5.044 | 374.173 | 277.320 | 31.715 | 0.492 | 1.812 |
| 760 | 26.269 | 37.205 | 167.580 | 19.947 | 1.000 | 0.136 |
| 760 | 22.066 | 70.728 | 253.080 | 25.342 | 0.840 | 0.257 |
| 760 | 14.711 | 149.744 | 303.120 | 30.994 | 0.560 | 0.544 |
| 760 | 13.660 | 246.083 | 345.660 | 38.183 | 0.520 | 0.894 |
| 760 | 12.609 | 374.173 | 349.980 | 45.221 | 0.480 | 1.360 |
| 950 | 49.912 | 36.949 | 188.580 | 25.491 | 1.000 | 0.107 |
| 950 | 39.404 | 70.256 | 274.620 | 31.619 | 0.789 | 0.204 |
| 950 | 27.583 | 149.724 | 342.840 | 39.532 | 0.553 | 0.436 |
| 950 | 24.956 | 246.083 | 375.960 | 48.217 | 0.500 | 0.715 |
| 950 | 22.329 | 374.173 | 419.040 | 56.421 | 0.447 | 1.087 |

(D) Temperature $40^{\circ} \mathrm{C}$
$c=8.82$
pH value 1.0
$\mathrm{a}=0.40$
$K_{L}{ }^{a}=c(H P / V)^{a}(V s)^{b}$
$\mathrm{b}=0.50$

| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{hrr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND} \frac{3}{\mathrm{I}} \\ & \times \quad 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 37.736 | 50.460 | 6.145 | 1.000 | 0.366 |
| 285 | 0.788 | 70.965 | 70.260 | 7.572 | 0.769 | 0.688 |
| 285 | 0.709 | 150.689 | 91.500 | 10.557 | 0.692 | 1.464 |
| 285 | 0.709 | 248.150 | 104.280 | 13.530 | 0.692 | 2.404 |
| 285 | 0.709 | 377.008 | 136.560 | 16.659 | 0.692 | 3.653 |
| 380 | 2.942 | 37.618 | 73.080 | 9.367 | 1.000 | 0.274 |
| 380 | 2.207 | 70.965 | 121.860 | 11.444 | 0.750 | 0.516 |
| 380 | 1.681 | 150.689 | 141.540 | 14.924 | 0.571 | 1.094 |
| 380 | 1.576 | 246.772 | 174.540 | 18.586 | 0.536 | 1.788 |
| 380 | 1.576 | 376.063 | 227.220 | 22.919 | 0.536 | 2.732 |
| 570 | 11.033 | 37.480 | 127.020 | 15.887 | 1.000 | 0.181 |
| 570 | 9.457 | 71.220 | 205.980 | 20.552 | 0.857 | 0.345 |
| 570 | 6.147 | 150.689 | 260.940 | 25.102 | 0.557 | 0.730 |
| 570 | 5.674 | 246.083 | 297.180 | 31.025 | 0.514 | 1.192 |
| 570 | 5.674 | 246.083 | 297.180 | 31.025 | 0.514 | 1.192 |
| 570 | 5.359 | 376.063 | 330.120 | 37.443 | 0.486 | 1.822 |
| 760 | 25.218 | 37.343 | 180.900 | 22.092 | 1.000 | 0.136 |
| 760 | 19.965 | 70.728 | 279.000 | 27.639 | 0.792 | 0.257 |
| 760 | 14.711 | 149.744 | 363.960 | 35.511 | 0.583 | 0.544 |
| 760 | 13.660 | 246.772 | 399.660 | 44.193 | 0.542 | 0.896 |
| 760 | 12.609 | 376.063 | 455.460 | 52.774 | 0.500 | 1.368 |
| 950 | 48.598 | 37.205 | 231.240 | 28.689 | 1.000 | 0.108 |
| 950 | 39.404 | 70.728 | 387.540 | 36.304 | 0.850 | 0.205 |
| 950 | 28.896 | 150.689 | 484.980 | 46.700 | 0.595 | 0.438 |
| 950 | 26.269 | 247.461 | 544.200 | 57.527 | 0.541 | 0.720 |
| 950 | 24.956 | 377.953 | 562.380 | 69.570 | 0.514 | 1.098 |

Temperature $40^{\circ} \mathrm{C}$
$\mathrm{c}=8.82$
pH value 1.5
$\mathrm{a}=0.40$
$\mathrm{K}_{\mathrm{L}} \mathrm{a}=\mathrm{c}(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}(\mathrm{Vs})^{\mathrm{b}}$

| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}{ }^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{\mathrm{a}} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{array}{r} \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ \times \quad 10^{2} \end{array}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 37.736 | 44.640 | 6.145 | 1.000 | 0.366 |
| 285 | 0.788 | 70.965 | 68.040 | 7.572 | 0.769 | 0.688 |
| 285 | 0.630 | 151.142 | 92.580 | 10.085 | 0.615 | 1.464 |
| 285 | 0.630 | 246.083 | 110.760 | 12.852 | 0.615 | 2.388 |
| 285 | 0.630 | 376.063 | 133.620 | 15.870 | 0.615 | 3.648 |
| 380 | 2.942 | 37.618 | 98.220 | 9.367 | 1.000 | 0.273 |
| 380 | 2.312 | 70.965 | 124.920 | 11.660 | 0.786 | 0.516 |
| 380 | 1.786 | 150.217 | 160.440 | 15.267 | 0.607 | 1.092 |
| 380 | 1.576 | 248.858 | 195.780 | 18.664 | 0.536 | 1.812 |
| 380 | 1.576 | 376.063 | 238.920 | 22.919 | 0.536 | 2.732 |
| 570 | 11.033 | 37.618 | 135.600 | 15.916 | 1.000 | 0.182 |
| 570 | 6.305 | 149.291 | 273.600 | 25.241 | 0.571 | 0.724 |
| 570 | 5.674 | 245.394 | 309.960 | 30.982 | 0.571 | 1.189 |
| 570 | 5.359 | 376.063 | 367.140 | 37.443 | 0.486 | 1.822 |
| 760 | 25.218 | 37.480 | 195.780 | 22.133 | 1.000 | 0.137 |
| 760 | 22.066 | 70.728 | 313.800 | 28.771 | 0.875 | 0.257 |
| 760 | 14.711 | 150.689 | 401.280 | 35.622 | 0.583 | 0.540 |
| 760 | 13.660 | 247.461 | 422.460 | 44.255 | 0.542 | 0.899 |
| 760 | 12.609 | 376.063 | 416.400 | 52.774 | 0.500 | 1.368 |
| 950 | 47.285 | 37.480 | 225.600 | 28.480 | 1.000 | 0.109 |
| 950 | 42.031 | 70.728 | 380.760 | 37.256 | 0.889 | 0.205 |
| 950 | 27.583 | 150.217 | 496.800 | 45.766 | 0.583 | 0.437 |
| 950 | 26.269 | 246.083 | 569.100 | 57.367 | 0.556 | 0.715 |
| 950 | 24.956 | 376.063 | 559.200 | 69.397 | 0.528 | 1.093 |


| Temperature $40^{\circ} \mathrm{C}$ | $\mathrm{c}=8.82$ |
| :--- | :--- |
| pH value 5.7 | $\mathrm{a}=0.40$ |
| $\mathrm{~K}_{\mathrm{L}} \mathrm{a}=\mathrm{c}(\mathrm{HP} / \mathrm{V})^{\mathrm{a}}(\mathrm{Vs})^{\mathrm{b}}$ | $\mathrm{b}=0.50$ |


| Agitation <br> Speed rpm | Power Input HP/1000 gals. | Superficial Vëlocity $\mathrm{ft} / \mathrm{hr}$ | $\mathrm{K}_{\mathrm{L}} \mathrm{a} \mathrm{hr}^{-1}$ | $\begin{aligned} & (\mathrm{HP})^{a} \\ & (\mathrm{Vs})^{\mathrm{b}} \end{aligned}$ | P/Po | $\begin{aligned} & \mathrm{Q} / \mathrm{ND}_{\mathrm{I}}^{3} \\ & \times 10^{2} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 285 | 1.024 | 37.736 | 41.640 | 6.145 | 1.000 | 0.366 |
| 285 | 0.788 | 71.220 | 66.060 | 7.586 | 0.769 | 0.828 |
| 285 | 0.709 | 150.689 | 86.160 | 10.557 | 0.692 | 1.464 |
| 285 | 0.630 | 247.461 | 93.000 | 12.888 | 0.615 | 2.398 |
| 285 | 0.630 | 375.118 | 121.200 | 15.850 | 0.615 | 3.636 |
| 380 | 2.942 | 37.618 | 70.440 | 9.367 | 1.000 | 0.274 |
| 380 | 2.102 | 69.488 | 107.520 | 11.105 | 0.714 | 0.505 |
| 380 | 1.576 | 151.142 | 141.000 | 14.564 | 0.536 | 1.098 |
| 380 | 1.576 | 247.461 | 172.380 | 18.612 | 0.536 | 1.800 |
| 380 | 1.471 | 376.063 | 188.340 | 22.293 | 0.500 | 2.732 |
| 570 | 11.821 | 0.000 | 1.440 | 0.000 | 1.000 | 0.000 |
| 570 | 11.033 | 37.618 | 122.160 | 15.916 | 0.933 | 0.182 |
| 570 | 9.457 | 69.252 | 189.780 | 20.268 | 0.800 | 0.336 |
| 570 | 6.305 | 150.689 | 222.060 | 25.358 | 0.533 | 0.730 |
| 570 | 5.674 | 247.461 | 266.220 | 31.111 | 0.480 | 1.200 |
| 570 | 5.359 | 361.870 | 295.320 | 36.733 | 0.453 | 1.752 |
| 760 | 26.269 | 0.000 | 3.000 | 0.000 | 1.000 | 0.000 |
| 760 | 25.218 | 37.618 | 156.900 | 22.173 | 0.960 | 0.137 |
| 760 | 21.015 | 70.965 | 244.500 | 28.260 | 0.800 | 0.258 |
| 760 | 14.711 | 150.689 | 297.300 | 35.622 | 0.560 | 0.540 |
| 760 | 13.660 | 246.772 | 334.080 | 44.193 | 0.520 | 0.804 |
| 760 | 12.609 | 377.953 | 333.540 | 52.906 | 0.480 | 1.368 |
| 950 | 49.912 | 0.000 | 4.800 | 0.000 | 1.000 | 0.000 |
| 950 | 42.031 | 70.965 | 308.040 | 37.318 | 0.842 | 0.206 |
| 950 | 28.896 | 150.689 | 336.000 | 46.700 | 0.579 | 0.438 |
| 950 | 26.269 | 246.772 | 363.660 | 57.447 | 0.526 | 0.718 |
| 950 | 23.642 | 376.063 | 412.920 | 67.908 | 0.474 | 1.093 |

## SULFITE OXIDATION PROCESS

Temperature $=35^{\circ} \mathrm{C}$ Shaft speed $=950 \mathrm{rpm}$

| $\begin{array}{\|l} \text { Superficial } \\ \text { Velocity } \\ \text { ft/hr } \end{array}$ | Power Input (HP/1000 ga1s) | Time <br> (min) | Sulfite Conc. (N) | $\begin{gathered} \mathrm{K}_{\mathrm{L}} \mathrm{a} \times 10^{-2} \\ \left(\mathrm{hr}^{-1}\right) \end{gathered}$ | Average $\begin{gathered} \left.K_{L} \times \mathrm{K}^{-1}\right) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 37.74 | 47.28 | 0.0 | 1.324 |  |  |
|  |  | 10.0 | 1.234 | 12.21 |  |
|  |  | 20.0 | 1.116 | 14.20 |  |
|  |  | 30.0 | 1.026 | 13.54 |  |
|  |  | 40.0 | 0.948 | 12.82 |  |
|  |  | 50.0 | 0.882 | 12.04 |  |
|  |  | 60.0 | 0.802 | 11.82 | 12.8 |
| 70.97 | 38.09 | 0.0 | 0.790 |  |  |
|  |  | 10.0 | 0.656 | 18.29 |  |
|  |  | 20.0 | 0.484 | 20.80 |  |
|  |  | 30.0 | 0.322 | 21.27 |  |
|  |  | 40.0 | 0.168 | 21.16 | 20.4 |
| 149.29 | 28.90 | 0.0 | 1.256 |  |  |
|  |  | 5.0 | 1.148 | 29.44 |  |
|  |  | 10.0 | 1.040 | 29.44 |  |
|  |  | 15.0 | 0.926 | 29.89 |  |
|  |  | 20.0 | 0.860 | 26.91 | 28.9 |
| 245.39 | 26.27 | 0.0 | 0.860 |  |  |
|  |  | 5.0 | 0.718 | 38.78 |  |
|  |  | 10.0 | 0.598 | 35.91 | 37.3 |
| 360.92 | 24.96 | 0.0 | 0.390 |  |  |
|  |  | 3.5 | 0.292 | 42.04 | 45.1 |
|  |  | 7.0 | 0.152 | 48.18 |  |
| 0.0 |  | 0.0 | 0.190 |  |  |
|  |  | 6.0 | 0.188 |  |  |
|  |  | 12.0 | 0.186 |  |  |

Temperature $=35^{\circ} \mathrm{C}$
Shaft speed $=570 \mathrm{rpm}$

| $\begin{gathered} \text { Superficial } \\ \text { Velocity } \\ \mathrm{ft} / \mathrm{hr} \end{gathered}$ | Power Input (HP/1000 gals) | Time (min) | Sulfite <br> Conc. (N) | $\begin{gathered} \mathrm{K}_{\mathrm{L}} \mathrm{a} \times 10^{-2} \\ \left(\mathrm{hr}^{-1}\right) \end{gathered}$ | $\begin{gathered} \text { Average } \\ \mathrm{K}_{\mathrm{L}} \mathrm{a} \times 10^{-2} \\ (\mathrm{hr}-1) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 36.55 | 10.56 | 0.0 | 1.212 |  |  |
|  |  | 0.6 | 1.192 | 6.07 |  |
|  |  | 20.0 | 1.122 | 6.63 |  |
|  |  | 40.0 | 1.048 | 10.40 | 6.24 |
| 67.14 | 9.46 | 0.0 | 1.046 |  |  |
|  |  | 10.0 | 0.962 | 10.44 |  |
|  |  | 20.0 | 0.910 | 9.89 | 10.17 |
| 140.46 | 6.30 | 0.0 | 0.910 |  |  |
|  |  | 8.0 | 0.864 | 6.24 |  |
|  |  | 15.0 | 0.806 | 8.56 | 7.40 |
| 227.38 | 5.52 | 0.0 | 0.806 |  |  |
|  |  | 8.0 | 0.740 | 13.00 |  |
|  |  | 15.0 | 0.668 | 12.90 | 12.1 |
| 344.83 | 5.20 | 0.0 | 0.668 |  |  |
|  |  | 8.0 | 0.594 | 12.00 |  |
|  |  | 15.0 | 0.526 | 12.60 | 12.3 |
| 0.0 |  | 0.0 | 0.526 |  |  |
|  |  | 15.0 | 0.516 | 15.0 |  |

Temperature $=35^{\circ} \mathrm{C}$
Shaft speed $=285 \mathrm{rpm}$

| Superficial Velocity $\mathrm{ft} / \mathrm{hr}$ | Power Input (HP/1000 gals) | $\begin{aligned} & \text { Time } \\ & (\min ) \end{aligned}$ | Sulfite <br> Conc. (N) | $\begin{gathered} \mathrm{K}_{\mathrm{L}} \mathrm{a} \times 10^{-2} \\ \left(\mathrm{hr}^{-1}\right) \end{gathered}$ | $\begin{gathered} \text { Average } \\ \mathrm{K}_{\mathrm{L}} \mathrm{a} \times 10^{-2} \\ \left(\mathrm{hr}^{-1}\right) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 38.01 | 0.71 | 0.0 | 1.318 |  |  |
|  |  | 10.0 | 1.298 | 2.73 |  |
|  |  | 31.0 | 1.286 | 1.43 | 2.08 |
| 71.21 | , 0.71 | 0.0 | 1.296 |  |  |
|  |  | 34.0 | 1.272 | 0.90 |  |
|  |  | 77.0 | 1.240 | 0.97 |  |
|  |  | 96.0 | 1.216 | 1.12 | 1.00 |
| 148.36 | 0.63 | 0.0 | 1.216 |  |  |
|  |  | 25.0 | 1.192 | 1.28 | 1.23 |
|  |  | 50.0 | 1.172 | 1.19 |  |
| 241.23 | 0.63 | 0.0 | 1.172 |  |  |
|  |  | 15.0 | 1.148 | 2.36 |  |
|  |  | 52.0 | 1.084 | 2.36 |  |
|  |  | 90.0 | 1.050 | 1.86 | 2.19 |
| 351.45 | 0.63 | 0.0 | 1.052 |  |  |
|  |  | 25.0 | 1.020 | 1.64 |  |
|  |  | 50.0 | 0.966 | 2.32 | 1.98 |
| 0.0 |  | 0.0 | 0.956 |  |  |
|  |  | 25.0 | 0.958 |  |  |


[^0]:    * unsaturated air

