# MIXING AND OXYGEN TRANSFER IN MINERAL BIOLEACHING

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Abstract - Mixers play an important function in the operation of bioleach reactors. They must suspend solids, transfer oxygen, maintain pH and temperature uniformity, assist in heat transfer, and avoid the development of excessive shear rates. Some of the principles used in mixer design to achieve these functions are discussed. The LIGHTNIN A315 impeller is effectively superceeding the older Rushton turbine in these operations.

The key part in the process which the mixer plays means that it must have a sound mechanical design to minimise failures and provide a long life.

Keywords- Agitator, mixer, mass transfer, oxygen transfer, impeller.

## Introduction

The oxidation of sulphide ores by bacterial action is commonly carried out in continuous stirred tank reactors (CSTR). The Biox® process developed by Genmin and described by van Aswegen, Godfrey, Miller, and Itaines (1991) illustrates the key part the reactor plays in this process. The mixer or agitator design is an important element in the process operation in the areas of solids suspension, oxygen transfer, pH and temperature uniformity, and heat transfer. Usually the mixer sizing is dictated by the transfer of oxygen from air introduced into the reactors, though the other processes are not inconsequential. Since the power required for the blowers and the mixers represents a major cost in the operation of the process it is important to optimise the design of the oxygen transfer process. This involves consideration of the required oxygen rate, dissolved oxygen level to be maintained, temperature, pressure, the effect of ore solids on oxygen transfer, tank size and shape, and the relative split between the air rate and the mixer power.

Since the reactor is such a key part in the process, it is essential that the mixers be designed for long term reliable operation to ensure a high percentage of practical plant availability. Mixers in gas-liquid-solids process experience special conditions which must be taken into account in their mechanical design.

This paper presents some of the considerations necessary to specify the process functions of the mixer as well as the mechanical design problems to be considered in the selection of the mixer.

## Process Requirements

There are a number of gas-liquid-solid mass transfer processes encountered in mineral processing. As Fraser (1992) described, these may be controlled by either the gas-liquid transfer step or by the liquid-solid step. Biological processes are relatively slow and, given an adequate oxygen and nutrient supply, controlled by the rate of bacterial action on the minerals. This rate is usually specific to the particular mineral/bacterial system and must be determined experimentally in a pilot plant. As Dew and Godfrey (1991) described, different mineral species may be oxidised at different rates. They also note that it may only be necessary to partially oxidise some mineral species. For example as little as 30% sulphide conversion may be adequate for gold liberation.

Once the rate and extent of conversion is determined the required oxygen demand can be estimated from the chemical stoichiometry of reaction of the various materials.

It is likely in most cases that the mixer/air rate design to satisfy this oxygen demand will control the sizing of the mixer. This will be discussed later in more detail. Assuming the oxygen demand is satisfied, can the mixer affect the rate of the process? It appears that once some basic requirements are met there is little further influence of the mixer on the rate. These basic requirements may be summarised as follows.

1) **Solids Suspension**

Obviously the solids must be suspended or at least moving to provide adequate contact with the solution containing the dissolved oxygen, nutrients etc.

2) **Heat Transfer**

Excess heat must be removed by fluid motion past heat transfer surfaces.

3) **pH and Temperature Uniformity**

The process rate is sensitive to these parameters. Variations within the reactor may be detrimental to the process rate.

4) **Dissolved Oxygen**

As well as meeting the minimum oxygen rate, the mixer/gas system must have the capacity to maintain a minimum dissolved oxygen level. It is a significant factor in the mixer design for oxygen transfer. However, Chapman et al (1990) found that above dissolved oxygen levels of 1 - 2 mg/l there was little improvement in the oxidation rate for a gold bearing, high *arsenic, sulphide concentrate.*

5) **Low Shear Rates**

Hackl and Wright (1989) found excessive tip speeds using Rushton turbine type impellers to be detrimental to the rate of bioleaching of a refractory gold ore. This parallels findings for other biological processes such as fermentation in the pharmaceutical industry. While the Rushton turbine remains an excellent gas dispersion impeller, the LIGHTNIN A315 which is designed for gas dispersion using an axial flow pattern rather than radial, has much lower maximum and average shear rates as is evident from Figures 3 and 4. In addition to other advantages this ensures there will be no detrimental effects of shear stress on the bacterial action.

***Mixer Impeller Selection***

While oxygen uptake rates in bioleaching are not usually high compared with processes such as pressure oxidation or fermentation process, they are usually sufficient to be the controlling parameter for mixer selection. Radial flow impellers such as the Rushton turbine are the traditional impellers for high gas dispersion rates. They have and can be used in bioleaching processes but there are a number of advantages in the use of axial flow impellers such as the LIGHTNIN A315 (see Figure 1) designed for gas dispersion operations.

Figure 2 illustrates the basic difference in flow pattern between the Rushton turbine and an axial flow pattern. The radial flow produces a zonation particularly when multiple impellers are used. This can be detrimental in biological process requiring close pH and temperature control.

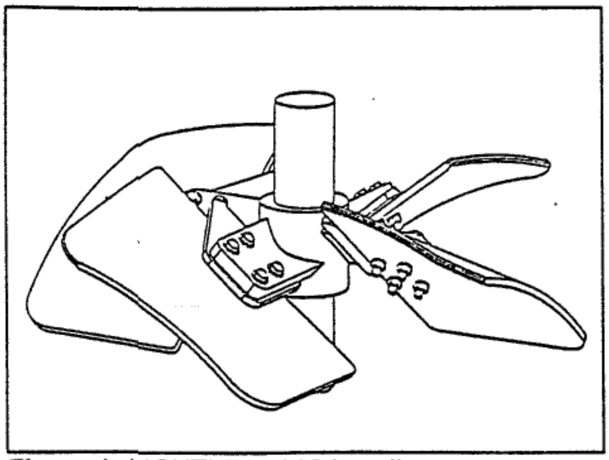

**Figure 1** LIGHTNIN A315 Impeller

The downward flow from axial flow impellers sweeps across the bottom of the tank and is the most efficient pattern for suspension of solids. Normally for gold bearing sulphide ores the power levels required for oxygen transfer mean solids can be suspended even with radial flows, but other systems with lower oxygen uptake rates and faster settling solids may require the axial down flow pattern to suspend solids.

Quantitative data on a typical Rushton turbine (LIGHTNIN R100) and a LIGHTNIN A315 impeller are shown in Figures 3 and 4. These are velocity vector diagrams generated by a laser doppler velocimeter described by Weetman and Salzman (1981). The vectors are shown on traverse lines across the tank. The data can be integrated over the impeller and total flow areas to provide quantitative flow data. Velocity changes over distance can also be examined to determine maximum and average impeller zone shear rates.

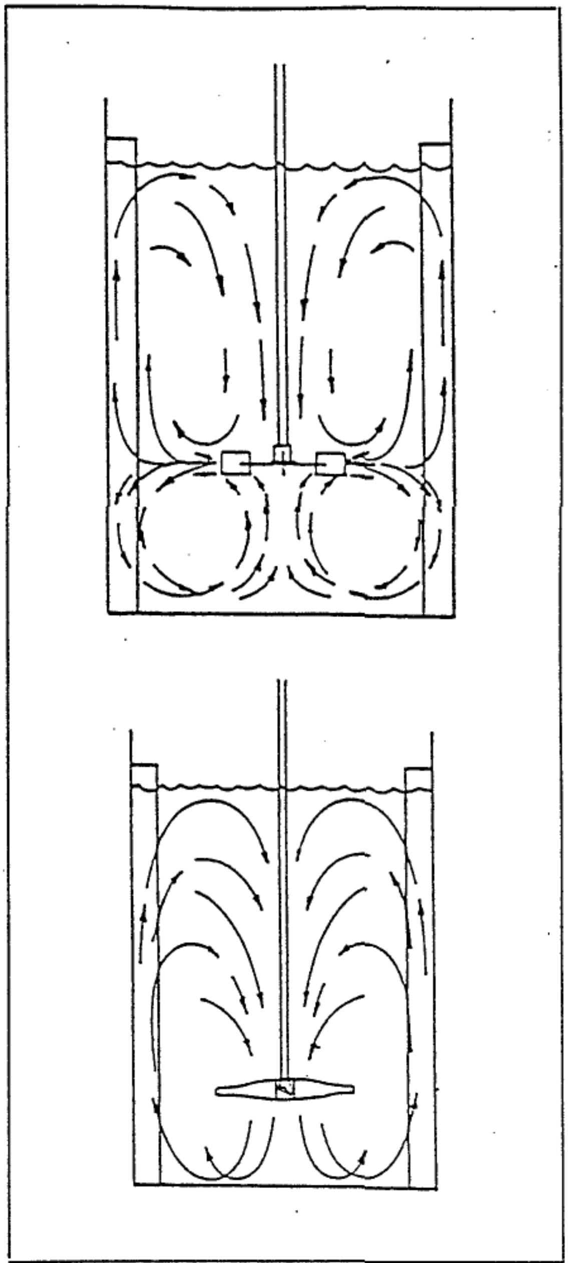

**Figure 2** Flow pattern of a Rushton turbine above compared with the preferrred axial flow for solids suspension in below.

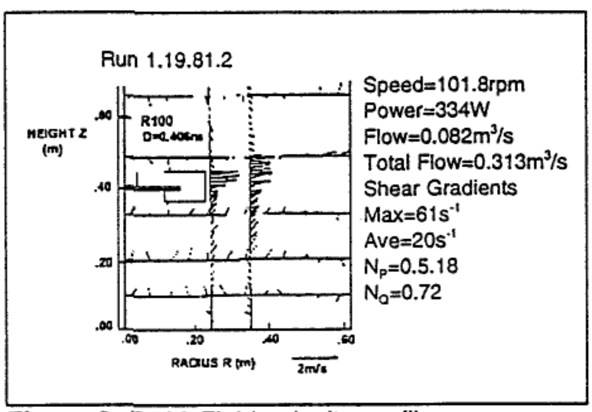


**Figure 3** R100 Fluid velocity profile

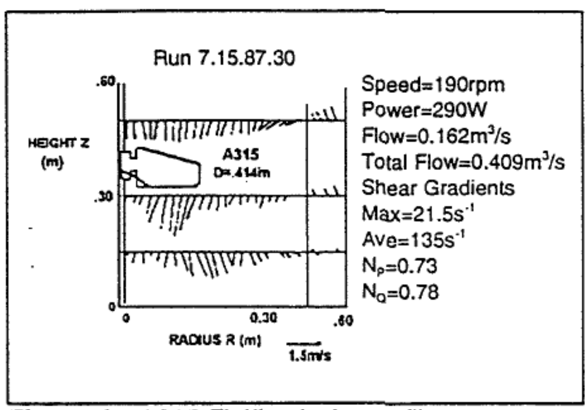


**Figure 4** A315 Fluid velocity profile

Impeller performance can be compared in different ways but a flow/power basis at constant flow and impeller diameter is shown in Table 1. The pitched blade turbine and LIGHTNIN A310 impellers are only suitable for very low gas dispersion rates and would not normally be suitable for bioleaching operations but are shown for interest. With the Rushton turbine most of the energy is dissipated in shear but with the LIGHTNIN A315 a high flow is produced. This is beneficial for solids suspension, reactor pH and temperature uniformity. It also results in high velocities past heat transfer surfaces thus minimising the area required.

**Table 1**

| Impeller Type | | | $(Q/P)_R$* |
|---|---|---|---|
| A200 | - | 45° Pitched Blade Turbine | 1.00 |
| A315 | - | Fluidfoil Gas Dispersion Impeller | 1.34 |
| A310 | - | Fluidfoil Impeller Axial Flow | 1.51 |
| R100 | - | Rushton Turbine Radial Flow | 0.18 |
| *$(Q/P)_R$ is ratio $(Q/P):(Q/P)_{A200}$ at constant Q and D | | | |

Shear rates or velocity gradients are also shown on the vector diagrams. Because of the different flow pattern the rates for the A315 may not be directly comparable with the Rushton turbine but are probably of the order of a third. Use of the A315 therefore avoids any problems with shear sensitive biological processes.

The power draw characteristics of the impellers also confirm benefits for the A315 impeller. As shown in Figures 3 and 4, the Rushton turbine has a much higher basic power number. This means that for a required developed power and impeller size it will have to operate at a much lower speed. This results in a higher torque gear drive. Since the size and costs of drives are related to torque significant first cost benefits are realised in this area by use of the A315.

Another important characteristic is the sensitivity of the impeller power draw to gas rate. The k factor or ratio of power with gas to power without gas, is shown for various impellers against an increasing gas rate in Figure 5.

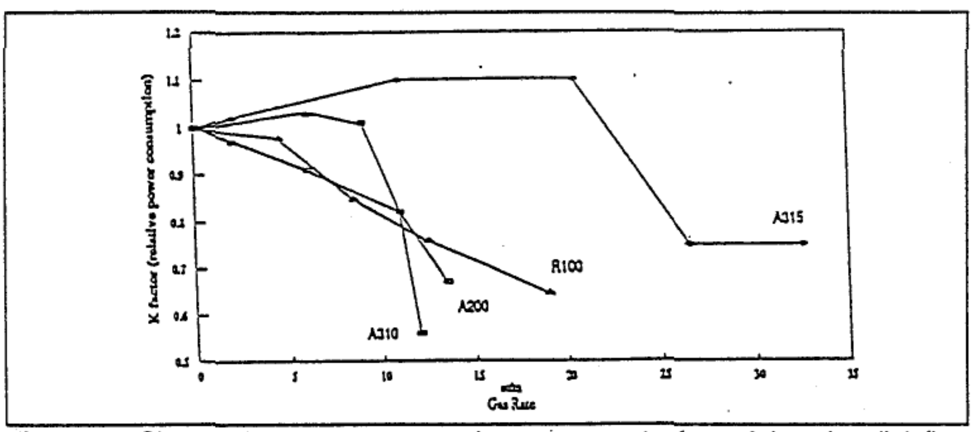


**Figure 5** Change in power consumption vs gas rate for axial and radial flow impellers.

There comes a point where eventually the liquid pumping action of the impeller is overwhelmed by the presence of the gas. This is termed flooding of the impeller. The Rushton turbine (R100) is affected by gas even at low gas rates. This might mean, for example, that at a typical operating point the impeller may be drawing only 60% of the power without gas. The implications for practical mixer design are two fold.

1) Design the mixer drive for the power at normal gas rate. This means that if it is not possible to operate the mixer without gas or even reduced gas rates because of overload - unless a two speed motor is employed.

2) Design the drive to operate ungassed. Then with gas at normal flow it will operate lightly loaded. This means drives are perhaps 60% larger than need be and costs are accordingly higher.

At the typical power levels of bioleaching and up to the flood point, the LIGHTNIN A315 has a relatively flat power draw characteristic within about 10% of the ungassed condition. Drives do not need to be significantly oversized to operate over the whole of the normal gas design range. This avoids the high cost of oversized drives.

## Oxygen Transfer

The gas-liquid oxygen transfer is often analysed by equations based upon the two film theory of mass transfer covered by chemical engineering texts.

Sparingly soluble gases such as oxygen are liquid film controlled and so the theory relates the rate of mass transfer to a mass transfer coefficient, a transfer area, and a concentration driving force in the liquid film.

$$R = k_L a\ (c* - c) \qquad (1)$$

The concentration driving force is normally expressed in liquid phase units.

Application of this equation to a gas rising in a mixed tank can be illustrated in Figure 6. $c^*$ is the liquid concentration in equilibrium with the gas. c is normally the value of dissolved oxygen to be maintained in the liquid. If it can be assumed that the liquid phase is well mixed then c remains constant throughout the tank. The gas, however, rises from the bottom to the top. Since $c^*$ is a function of temperature, pressure and the gas composition of the bubble it will change from bottom to top. At the bottom $c^*$ will be increased by the hydrostatic head (which is significant in large scale atmospheric tanks). When the gas is air, the bubble reaching the top will be partially stripped of oxygen and so the value of $c^*$ will be reduced. The LIGHTNIN organisation [Oldshue (1970), Fraser (1983)] generally uses the log mean of the driving force at the sparge and the surface.

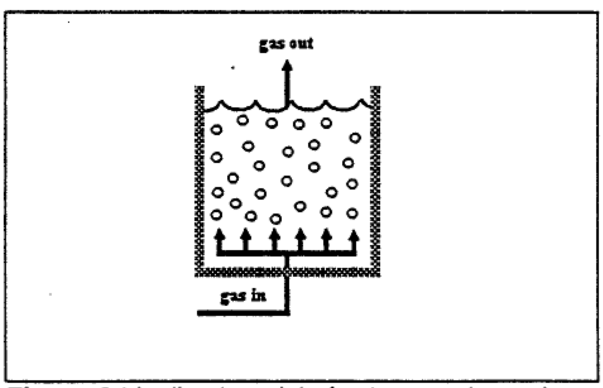


**Figure 6** Idealised model of submerged aeration

$$R = k_L a\ (c* - c)\, LM \qquad (2)$$

The effect of this correction is important in typical full scale industrial tanks.

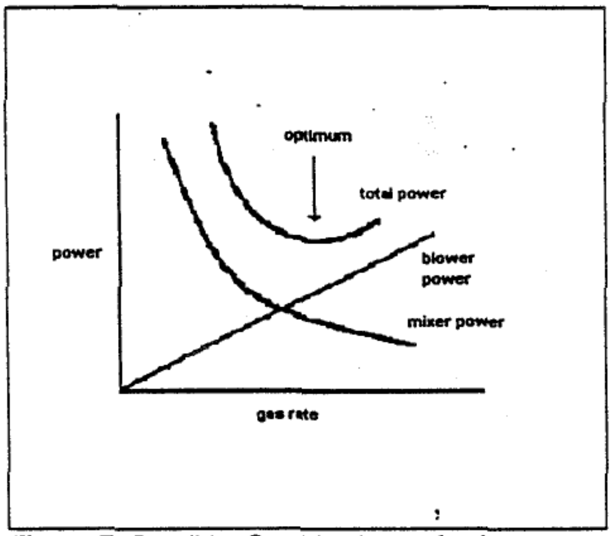


**Figure 7** Possible Combinations of mixer power and gas at fixed $K_La$

For oxygen in pure water c* can be obtained from Henry's law or handbook tabulations. In mineral slurries this is likely to be decreased by the presence of solids and salts in solution and the effect should be measured for each system under consideration. The ratio is often expressed as a beta factor.

$$\beta = \frac{c_* \ system}{c_* \ water} \tag{3}$$

It is not usually possible to separate the mass transfer coefficient, $k_L$ and the transfer area, a. Determination of a combined $k_La$, even in clean water, is difficult. Results need to be evaluated with caution especially when comparisons are made using different measurement techniques.

A good deal of work has been done in standardising test procedures for $k_La$ determination in clean water, particularly for applications in the waste water treatment field (see for example the ASCE test procedure).

However in this field uptake rates are typically an order of magnitude lower and these techniques present some problems when applied to the rates in bioleach systems. They are also usually carried out at typical ambient temperatures and then corrected to 20°C. This correction is normally small. However, as with most transfer processes there is a significant increase in $k_La$ with temperature, though there is limited data available at typical bioleach temperatures of 35 - 45°C. Actual system operating data is the best guide. It should also be noted that the rate increase is partly offset by the decrease in oxygen solubility and hence c* at the higher temperatures.

The air/water system is sometimes referred to as a coalescing system. The presence of salts and solids especially where they change surface tension or viscosity will change the rate compared with clean water. These systems are sometimes referred to as non-coalescing. The ratio is commonly expressed as an alpha factor.

$$\alpha = \frac{k_La \ system}{k_La \ water} \tag{4}$$

Inert regular solids such as glass beads have the effect of reducing the $k_La$, i.e. $\alpha$ is less than 1.0 (see for example Mills et al (1987)). Dissolved salts and other materials can increase the $k_La$. For example Smith et al (1977) found that $\alpha$ had a value of 2.0 for a Rushton turbine in an electrolyte solution. Machon, McFarlane and Nienow (1991) showed that gas hold-up could be significantly enhanced with axial flow impellers, where coalescence is severely inhibited.

The implications are that specific studies in the particular systems are necessary to quantify oxygen transfer rates. Genmin and LIGHTNIN have a joint development program which examines some of these effects for bioleach systems.

*For the dispersion of gas by a mixing impeller,* $k_La$ *has been correlated [e.g. Oldshue (1970)] in the* form:

$$k_La = x\,(P_G/V)^y\,(F)^z \tag{5}$$

x is a function of the type of impeller and the physical system.

y and z depend on the impeller type, and the scale of the operations. They need to be determined experimentally. LIGHTNIN have developed correlations of this type large scale submerged turbine water test data and from practical operating systems over a wide range of the variables.

A consequence of the general form of the correlation is that a required $k_La$ can be achieved by a variety of combinations of mixer powers and air rates. The air supply requires power to compress and so an optimum total power (sum of mixer and compressor) can be determined as shown in Figure 7.

When equation [5] is combined with equation [2] the resulting model is able to predict the effects of changes of system scale as well as the effects of the variables in Figure 3. For example increasing tank size but of the same shape will increase the pressure at the bottom of the tank due to the hydrostatic head and thus increase $c^*$ at the tank bottom, thus increasing the mass transfer rate. A change in the tank shape will also change the pressure or hydrostatic head. In addition the superficial velocity F will change due to a change in tank area. Initially it would appear beneficial to use a tall slim tank to increase superficial velocity and head. However it must be noted that the increased hydrostatic head will result in increased pressure required of the blower. This requires greater blower power. The savings in mixer power or air rate through a reduction in required $k_La$ will largely be offset by increased blower power. Figure 8 shows hypothetical examples using this type of analysis for a tank with a 1:1 height/diameter ratio and one with a 2:1 height/diameter ratio - volume and process parameters are the same. The 2:1 tank can reduce air flow through greater oxygen stripping efficiency but the higher head increases the blower power so that on a total power basis there is little difference provided by the changed configuration. This example has used a constant blower efficiency and any real situation should be reviewed using actual efficiencies to optimise the tank shape and mixer versus blower sizing split.

References are sometimes made to the amount of oxygen extracted from the available supply or the stripping efficiency. This is defined by:

$$E = \frac{RV}{0.3G} \tag{6}$$

In itself the oxygen stripping efficiency is not a good correlating parameter for mixer/air system performance. In the calculation of the log mean saturation value it is useful however to calculate the

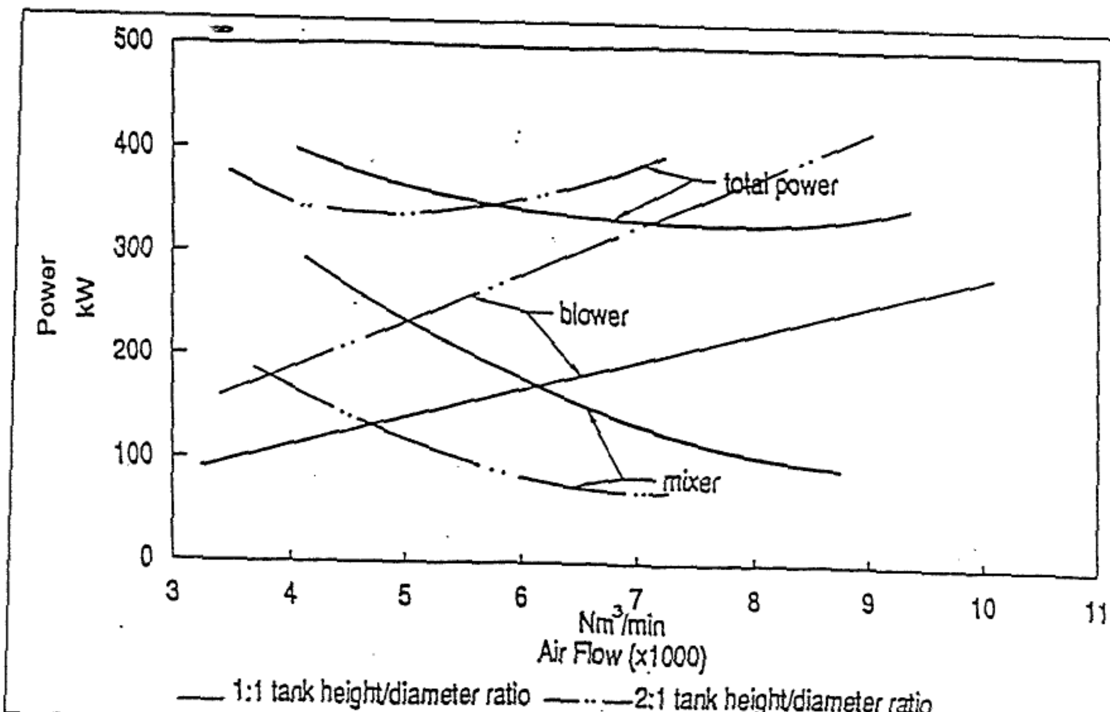


**Figure 8** Power vs air flow comparison.

equilibrium saturation value at the top of the tank by the relationship

$$Ytop = \frac{1-E}{4.76-E} \tag{7}$$

Normal air (E=0) has a mole or volume fraction of 0.21 oxygen. The equilibrium saturation value in contact with this stripped air is then $Y_{top}$/0.21 times the normal value in contact with air.

## Mixer Mechanical Design

The view that shafts and impellers can be designed for torque and weight and driven by a standard power transmission gearbox with an adequate service factor, is simplistic and inadequate. This is because there are significant additional forces of a fluctuating nature generated by the interaction of the impeller with the turbulent flow within the mixed tank. Additional forces are generated when gas is introduced to the liquid medium.

A comprehensive design will take into account the nature of these additional loads on each of the elements of the mixer. LIGHTNIN has measured and correlated these forces for its own standard impellers under a variety of fluid regimes. The details are proprietary but some comment on major elements may be helpful.

### Blade Forces

As Weetman and Oldshue (1988) showed the outlet velocities from mixing impeller blades show rapid fluctuations over time periods of less than 1 second. This results in corresponding mechanical load fluctuations on the blades of mixing impellers.

These can be measured by attaching multiple strain gauges to the surfaces of experimental blades.

Where gas is also present in significant quantities additional forces can be generated on the blades. In these circumstances fluctuations can be as high as plus or minus 100 percent.

### Shaft Forces

The outlet velocity fluctuations combined with the random "swirls and whirls" within a closely confined flow container (the tank) produce asymmetrics in the flow field which cause unsteady forces on the impeller. The most difficult component to handle is that operating at right angles to the shaft tending to bend it. These are in addition to the torque and weight down.

These forces can be measured using strain gauged spool pieces in test shafts as described by Salzman et al (1983). The forces can be correlated for each impeller type versus speed, diameter and the fluid regime. These can be used to predict forces in mixer designs using this type of impeller.

The shaft is therefore subject to the combined loads of torque and bending which can be separated into a static and fluctuating components. The shaft must be below the yield point for short term maximum load and below the fatigue limit for infinite life in a cyclic environment. A modified Goodman or failure diagram is necessary to analyse the combined loads. Oldshue (1983) describes some of the principles involved.

In addition the shaft is an elastic member supported at the top and with a weight (the impeller) at the bottom. This assembly has a natural frequency of vibration which is normally termed the critical speed. When operated near the critical speed small shaft deflections are magnified especially when operating in air. Operation in a liquid dampens but does not eliminate the amplification factor. At critical speed in air deflections grow to destructive levels so it is important to ensure this is not an operating condition.

A number of simple formulae are available for calculating critical speeds of single diameter shafts.

Practical designs become more complex and are best handled by a computer.

**Mixer Drives (Gearboxes)**

The ability to transmit the required torsional power from the prime mover (usually an electric motor) and reduce it to the appropriate speed at the mixer shaft is well covered in texts on the subject.

Ratings may be developed by the use of standards such as the American Gear Manufacturers Association (AGMA), though it is advisable to check a specific design type under test load conditions. Further comments on basic gearbox design will not be given here.

However the long centrelevered mixer shaft imposes significant loads on the gearbox whenever an independent mixer-shaft support system is not used. Normal "catalogue type" units are not usually able to withstand the large bending and down loads of the long overhung shafts.

It should be noted that AGMA ratings relate only to the transmitted power and do not take into account these additional loads. If these additional loads result in significant deflection of the casing, the ratings will not relate in any real way to the actual life of the gearbox. Reputable mixer manufacturers produce gearboxes with design capable of withstanding the total loads imposed on the box.

A typical mixer drive is shown in Figure 9. Some features incorporated in this design follow.

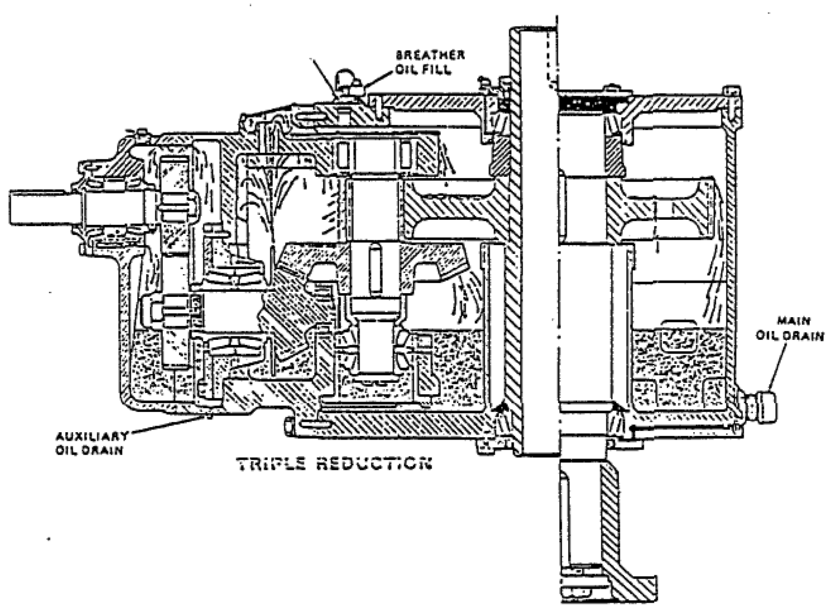


**Figure 9** A typical gearbox designed for mixer service

- Oil splash lubrication of all but the low speed shaft bearings.
- Oil retention around the output shaft by a dry well. Any eventual failure of the low speed bearing or oil seal does not result in general loss of oil. It also prevents oil contamination of the tank contents - an important consideration in many processes.
- A right angle drive for convenient motor mounting.
- A high strength casing to take the additional bending and down loads within allowable gear deflections.
- A large output shaft and support bearings.

- A vertical split casing which allows removal of all gears and bearings apart from the low *speed gear. This permits workshop maintenance on most components without* disconnecting the drive from the mixer shaft.

In this day and age drives should be of spiral bevel and helical gearing in order to maximise the power transmission and minimise energy losses. This also simplifies heat dissipation and raises thermal ratings.

Overall mixer design requires a knowledge of the loads generated by particular impeller designs *under liquid and gas operating regimes. Drives must have high overhung* load *capabilities* with known and proven limits to provide acceptable gear and bearing life.

**Nomenclature**

| | | |
|---|---|---|
| a | Specific transfer area | $m^2/m^3$ |
| A | Reactor cross sectional area | $m^2$ |
| c | Concentration of material in liquid | $kg/m^3$ |
| c* | Saturation concentration in equilibrium with the gas | $kg/m^3$ |
| D | Impeller diameter | m |
| E | Fraction of oxygen removed or stripping efficiency | - |
| F | Superficial gas velocity at mid depth G/A | $m^3/m^2/sec$ |
| G | Gas flow | $Nm^3/sec$ |
| $k_L$ | Specific mass transfer coefficient per unit area | m/sec |
| $k_La$ | Specific mass transfer coefficient | $sec^{-1}$ |
| k | ratio of gassed power/ungassed power $P_G/P_{GU}$ | - |
| N | Impeller rotational speed | $sec^{-1}$ |
| $N_P$ | Impeller power number $P/\rho N^3D^5$ | dimensionless |
| $N_Q$ | Impeller primary flow number $Q/ND^3$ | dimensionless |
| P | Power | kilowatts |
| Q | Impeller primary pumping rate | $m^3/sec$ |
| R | Volumetric mass transfer rate | kg/sec $m^3$ |
| V | Reactor volume | $m^3$ |
| $\rho$ | Liquid specific gravity | - |
| Y | Mole or volume fraction of $O_2$ in air | - |

**Subscripts**

| | |
|---|---|
| G | Gassed operation |
| L | Liquid phase |
| UG | Ungassed operation |
| top | top of tank |

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