

# A comparison of axial-flow impellers with inclined-blade turbines in a baffled mixer

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## SYNOPSIS

This study was aimed at a comparison of the effectiveness of a new axial-flow type of mixer impeller (the Prochem design) with the traditional inclined-blade turbine. The intended application of the mixers was in carbon-in-pulp plants for the extraction of gold from cyanide-leached pulps.

The first part of the project involved water and ion-exchange resin, and measurement of the power drawn by the various sizes of impeller to fully suspend the resin. The rate of reaction between the resin and the solution was measured as a function of the power input to the mixer.

In the second part of the project, use was made of activated carbon, silver cyanide solutions, and ore pulps. The rate of absorption of silver from the solutions and pulps was determined, as well as the rate of attrition of the activated carbon caused by the various impellers in clear water.

The Prochem design of axial-flow impeller was shown to fully suspend solids at only one-quarter of the power required by an inclined-blade turbine of similar size. The axial-flow pattern produced was responsible for the more uniform vertical concentration profile of suspended beads produced by the Prochem design.

These measurements verified the observations of other researchers that the rate of reaction is not affected by the design of impeller *provided that all the solids are fully suspended*. The Prochem design of impeller therefore achieved the same reaction rate as the conventional turbine at a quarter of the power input.

The attrition rates of activated carbon could be correlated, in terms of the energy absorbed, by the same equation for all the impellers. Higher concentrations of activated carbon increased the amount of carbon fines produced. These results emphasize the importance of designing mixers for minimum power consumption.

## SAMEVATTING

Die doel van hierdie studie was om die doeltreffendheid van 'n nuwe aksiale vloei mengstuur (die Prochem-ontwerp) met dié van die tradisionele skuinsbladturbine te vergelyk. Die beoogde aanwending van die mengers was in koolstof-in-pulpaanlegte vir die ekstraksie van goud uit pulp wat met sianied gelooë is.

Die eerste deel van die projek het water en ionruilars en die meting van die krag wat die verskillende grootte stuurers getrek het om die hars ten volle in suspensie te kry, behels. Die reaksietempo tussen die hars en die oplossing is gemeet as 'n funksie van die kraginset na die menging.

In die tweede deel van die projek is daar van geaktiveerde koolstof, silwersianiedoplossings en ertspulp gebruik gemaak. Die absorpsietempo van silwer uit die oplossings en pulp, asook die afslytt tempo van die geaktiveerde koolstof wat deur die verskillende stuurers in helder water veroorsaak is, is bepaal.

Daar is getoon dat die aksiale vloei stuurer met die Prochem-ontwerp net 'n kwart van die krag wat dieselfde grootte skuinsbladturbine nodig het, gebruik om vaste stowwe ten volle in suspensie te kry. Die aksiale vloei patroon wat bewerkstellig is, was verantwoordelik vir die meer eenvormige vertikale konsentrasieprofiel van gesuspendeerde pèrels wat met die Prochem-ontwerp verkry is.

Hierdie metings het ander navorsers se waarnemings dat die reaksietempo nie deur die ontwerp van die stuurer beïnvloed word nie, *mits al die vaste stowwe ten volle gesuspendeer is*, bevestig. Die stuurer met die Prochem-ontwerp het dus met 'n kwart van die kraginset dieselfde reaksietempo as die konvensionele turbine verkry.

Die afslytt tempo van geaktiveerde koolstof kon, in terme van die energie geabsorbeer, deur dieselfde vergelyking vir al die stuurers gekorreleer word. Hoër konsentrasies geaktiveerde koolstof het die hoeveelheid fynkoolstof wat voortgebring is, vermeerder. Hierdie resultate het die belangrikheid daarvan om mengers vir die minimum kragverbruik te ontwerp benadruk.

## Introduction

Slurries of milled ore in water are mixed in mechanically stirred tanks in many operations in the metallurgical and chemical industries. Such mixers are superseding the older air-driven pachuca or Browns tanks owing to their lower power consumption. The performance of these mixers is critically dependent on the design of the impeller in relation to the tank.

In the work described here, a comparison was made between modern axial-flow impellers developed by Prochem<sup>1</sup> and conventional turbines based on inclined flat

blades. The Prochem impellers were being considered for use in mixers in the carbon-in-pulp process for the extraction of gold from cyanide-leached pulps.

The two designs of impeller were compared on pilot-plant scale: firstly, in relation to their hydraulic behaviour; then, in relation to the rate of reaction between aqueous solution and suspended ion-exchange resin, and between ore slurry and suspended activated carbon; and, finally, in relation to the rate of attrition of activated carbon suspended in clear water.

The nomenclature used is listed at the end of the paper.

## Theoretical Background

### Power Drawn by the Mixer

The theoretical hydraulic power,  $P_H$ , drawn by the impeller of a mixer is given by the well-known expression

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$$P_H = \rho N^3 D^5 \dots\dots\dots (1)$$

The ratio of the actual hydraulic power for any mixer,  $P$ , to the theoretical hydraulic power at the same speed is defined as the power number  $N_p = P/P_H$ . The power number is normally correlated in terms of the Reynolds number for the mixer,  $Re = D^2 n \rho / \mu$ .

Several books on mixing<sup>2-5</sup> present curves for many different designs of impeller. These show that the power number becomes independent of Reynolds number under fully turbulent conditions.

*Hydraulic Power to Suspend Solids in a Mixer*

The primary function of a mixer when handling a slurry is to suspend the solids. If the solids are suspended, the reactions with the solids take place effectively. It is not necessary to achieve a completely homogeneous suspension. Consequently, the most important criterion for the design of such a mixer is the power required for the suspension of solids.

Cloete and Coetzee<sup>6</sup> have shown that the minimum power to achieve the suspension of solids in a mixer,  $P_{min}$ , can be derived theoretically from a consideration of only the mass of solids in the mixer,  $M_s$ , the density of the solids,  $\rho_s$ , of the liquid  $\rho$ , and the minimum fluidizing velocity of the solids in the liquid,  $U_{mf}$ .

$$P_{min} = g[(\rho_s - \rho)/\rho_s] M_s U_{mf} \dots\dots\dots (2)$$

The ratio of the actual power used by a mixer to the theoretical minimum power,  $P_{JS}/P_{min}$ , can be used to measure the efficiency of that particular design of mixer. Values of this ratio can range<sup>6</sup> from about 70 to over 500.

The values of the power ratio mentioned above indicate that real mixers are extremely inefficient when compared with the theoretical minimum power required. Hence, empirical correlations are needed to predict actual power requirements. Although recent books by Oldshue<sup>4</sup> and Harnby *et al.*<sup>5</sup> summarize nine and twelve such correlations respectively, Zwietering's correlation<sup>7</sup> is still generally useful.

*Mass Transfer Rates*

The overall rate of the reaction of solids with a liquid in a mixer depends on the various steps in the reaction. These steps normally comprise mass transfer in the liquid to the surface of the solids, followed by diffusion through the solid particles. The design of the mixer can affect only the rate of mass transfer through the liquid.

Reaction rates were measured as follows: an ion-exchange resin in the hydrogen form was neutralized with sodium hydroxide and, as mass transfer through the liquid film is known to be the rate-controlling step, the mass transfer rates are identical to the overall reaction rates.

Mass transfer rates between liquids and particles are usually correlated by the familiar Frössling equation given below:

$$Sh = 2 + 0,72 (Re_p)^{0,5} (Sc)^{0,33} \dots\dots\dots (3)$$

The Sherwood number,  $Sh$ , contains the mass transfer coefficient,  $K_L$ , while the Reynolds number of the particle,  $Re_p$ , contains the relative velocity between particles and liquid,  $U_R$ . However, it is impossible to measure this velocity directly in a stirred tank.

The assumption was made that the relative velocity between particles and liquid was proportional to the notional velocity generated by the impeller,  $ND$ . This was then substituted in the Reynolds number,  $Re_p$ , so that equation (3) predicts that the mass transfer coefficient will be proportional to the speed of the mixer,  $N$ , to the exponent 0,5 for any given impeller diameter,  $D$ .

Under turbulent conditions, the power drawn is proportional to the speed to the exponent 3 as given by equation (1). Alternatively, the speed can be described as being proportional to the power to the exponent  $1/3$ . Hence, the mass transfer coefficient should be proportional to the power to the exponent  $0,5 \times 1/3 = 0,15$ .

Harriott<sup>8</sup>, Sanger and Deckwer<sup>9</sup>, Levins and Glasbury<sup>10</sup>, and Oyama and Endoh<sup>11</sup> used various mixer geometries and mass transfer systems to determine the effect of power on the mass transfer coefficient,  $K_L$ . They found that  $K_L$  was proportional to the power to the exponent of between 0,1 and 0,3, which supports the value of 0,15 deduced from equations (1) and (3).

Davies<sup>12</sup> derived the following plot from published data:

$$\{Sh_{JS}/Sc^{0,33}\} \text{ against } \{d_p^{1,125}(\Delta\rho/\rho)^{0,375}\}.$$

From this, a value for the system used here can be calculated.

By use of the data from Table II, it was found that the mass transfer coefficient when resin beads were just suspended,  $K_{LJS}$ , was  $9,3 \times 10^{-5}$  m/s.

An alternative prediction based on the same data was made from equation (3) with the corrections noted by Nienow<sup>13,14</sup> for the estimation of  $K_{LJS}$  as  $10,2 \times 10^{-5}$  m/s.

**Experimental**

*Test Rig*

An assembly sketch of the complete unit is given in Fig. 1. An experimental cylindrical mixer was made up from 6 mm clear PVC sheet. The cylinder had an internal diameter of 420 mm with a flat base, and four vertical radial baffles of width 35 mm were fixed to the walls at 90-degree intervals. The baffles did not extend below a level of 110 mm above the base. The joint between the walls and the base was filleted to a radius of about 30 mm. A depth of liquid equal to the diameter of the tank was used in all the experiments.

The mixer shaft was mounted axially in the tank and was driven by a variable-speed electric motor. The motor, drive, and gearbox formed a unit that was suspended from a thin multistrand steel cable and located horizontally by two steadying bearings. The operation of the mixer caused the drive unit to rotate slightly in its bearings and indicate torque on a spring scale. The power drawn by the impeller was derived simply from the torque and shaft speed measured with a tachometer.

The mixer was designed to carry Prochem axial-flow impellers of various sizes and standard inclined-blade turbines. Photographs of the two series of impellers are shown in Figs. 2 and 3. A summary of the important dimensions of the mixer and impellers appears in Table I. Only the results of the medium-sized turbine, which is of similar diameter to the largest Prochem impeller, are reported here.

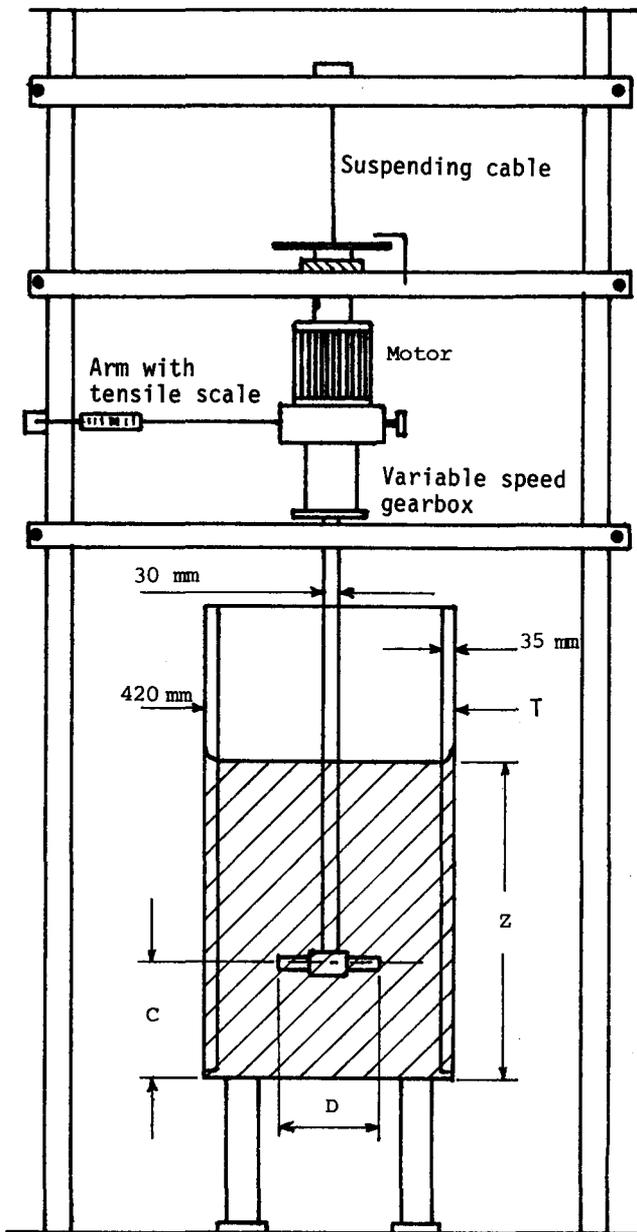


Fig. 1—Outline sketch of the experimental mixer

**Solid-Liquid System**

The experiments on the suspension of solids in water were carried out with a strongly cationic resin (Rohm & Haas IR 120). The ion-exchange resin was selected as a test solid since the particles are almost spherical. The properties of the resin are given in Table II.

**Measurement of Solids Concentration**

Fluctuations of the concentration due to turbulence were observed. An optical detector was built to measure the solids concentration at a point in the mixer so that the concentration profile could be studied. The detector was based on a torch bulb and light-sensitive resistor. The light-sensitive resistor was placed in a bridge circuit, and the out-of-balance voltage signal was measured as a function of the resin concentration.

These signals were converted to light intensity,  $I$ , by the use of the manufacturer's data for the resistance. The data were well-correlated by equation (4) to express the volumetric concentration of the resin,  $X_v$ , in terms of the ratio of light intensities,  $(I_0/I)$ , as described by Coetzee<sup>15</sup>.

$$\log (I_0/I) = K_i X_v \dots\dots\dots (4)$$

During calibration, the detector output was displayed on an oscilloscope, which showed the fluctuations clearly. An irregular waveform with a period of about 1,5 seconds was observed. The following technique was developed to take an average of this value.

The signal was fed to a Hewlett-Packard 3497A Data Acquisition Control Unit through an 82937A HP-IB interface and an HP-85 personal computer. The computer took a series of 1000 readings at intervals of 50 ms, which were stored by the data-acquisition unit. This set of readings was read back by the computer and the arithmetic average calculated. This procedure was repeated five to ten times, and a final average was calculated to give the average volumetric concentration of resin at that point.

**Solids Concentration Profile**

The optical detector was used to measure the vertical

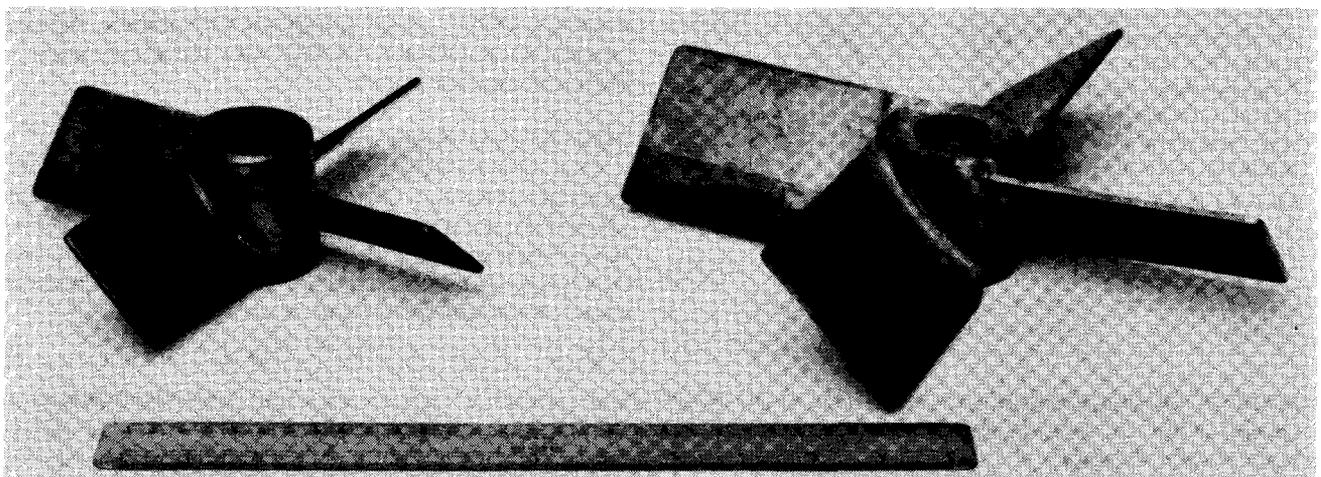


Fig. 2—Turbine impellers with blades inclined at 45 degrees D 200 mm Medium D 270 mm Large

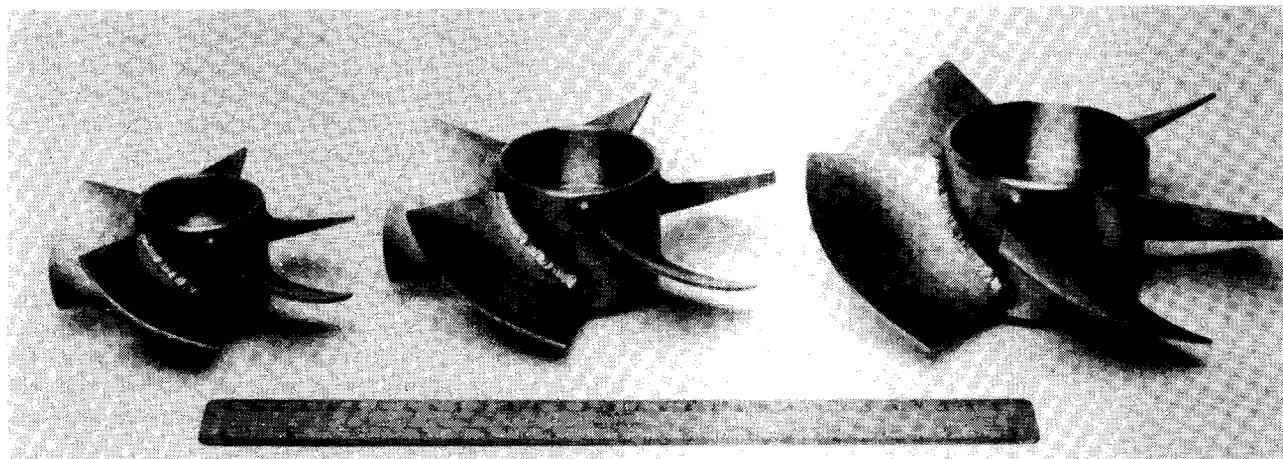


Fig. 3—Prochem impellers (the flow direction is upwards in the photograph) D 126 mm Small D 167 mm Medium D 202 mm Large

TABLE I  
DIMENSIONS OF TANK AND IMPELLERS

<i>Cylindrical Tank</i>			
Internal diameter (mm)			420
Overall depth (mm)			1050
Wall thickness (mm)			6
Width of 4 baffles (mm)			35
<i>Prochem Impellers</i>			
	<i>Small</i>	<i>Medium</i>	<i>Large</i>
Diameter (mm)	126	167	202
Tank/impeller diameter	3,33	2,52	2,08
<i>Turbines with 45° Inclined Blades</i>			
		<i>Medium</i>	<i>Large</i>
Diameter (mm)		200	270
Tank/turbine diameter		2,10	1,56
Number of blades		4	4
Length of blades (mm)		73	107
Width projected vertically (mm)		38	54,5

TABLE II  
PROPERTIES OF SOLIDS AND SLURRY

Parameter	Ion-exchange resin	Activated carbon
Moist particle density (kg/m <sup>3</sup> )	1270	1230
Size range for mass transfer (mm)	0,55–0,88	1,4–1,7
Average size (mm)	0,71	1,57
Terminal velocity in water (mm/s)	28	74
Size range for attrition runs (mm)	—	1,0–2,8
Ionic capacity of resin (meq/g)	4,4	
Diffusivity of NaOH (m <sup>2</sup> /s)	2,13 × 10 <sup>-9</sup>	
<i>Slurry of ERPM Mine Residue</i>		
Density of ore slurry (kg/m <sup>3</sup> )	1460	
Viscosity of ore slurry (kg/m·s)	4,0 × 10 <sup>-3</sup>	
Ion-exchange Resin: Rohm & Haas IR 120, strong cation		
Activated Carbon: Le Carbone G210 AS		

profile of solids concentration as a function of the mixer speed for the two types of impeller studied, as described below under **Results**.

#### Determination of Solids' Just-suspension

This important criterion in studies on mixers has been

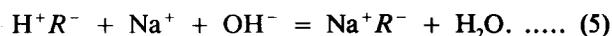
accepted by most workers as the point at which no particles are seen to rest for more than about one second on the base of a transparent tank. This was based on visual observation and was consequently prone to operator error. Other workers such as Musil *et al.*<sup>16</sup>, Kolar<sup>17</sup>, and Cliff *et al.*<sup>18</sup> used instrumental methods to measure the concentration of solids at a fixed point in the tank. However, reasonably good agreement between the two techniques was obtained.

The technique used here was based on the measurement of the solids concentration at a point 20 mm above the base. This value increased with mixer speed until all the solids were just suspended. It then reached a clearly defined maximum. The subsequent decrease in concentration with increasing speed was due to solids becoming more evenly distributed throughout the rest of the vessel. This technique is also described by Nienow in a recent book<sup>14</sup>.

The results of two typical measurements are shown in Fig. 4 compared with the speed for just suspension from visual observation. By use of the instrumental method, values of the speed for just suspending particles,  $N_{JS}$ , could be repeated within 2 to 3 per cent. It is clear that the maxima of the curves correspond to the visual determination of  $N_{JS}$ , which is indicated by arrows. All subsequent measurements of  $N_{JS}$  were therefore made by means of optical signals.

#### Mass Transfer Rates to Ion-exchange Resin

The neutralization of cation-exchange resin in the hydrogen form by a dilute solution of sodium hydroxide takes place following the overall reaction shown below. It is of first order, with a rate proportional to the concentration of sodium hydroxide in solution, provided that excess hydrogen-form resin is present.



The symbol  $R^-$  represents a unit ionic fixed charge on the polymer matrix of the resin. The exchange of  $Na^+$  for  $H^+$  ions at active sites in the resin leads to the formation of water molecules. The appropriate liquid-phase diffusion coefficient for sodium hydroxide,  $d$ , is the combined one of the two ions using Nernst's equation

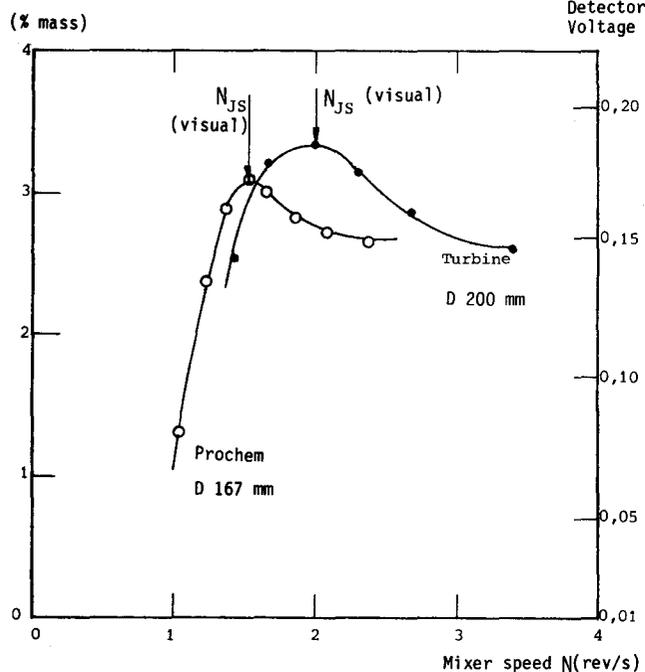


Fig. 4—Resin content 20 mm above the base of the tank versus mixer speed for TIC = 4

$$d = 2(d^+ \times d^-)/(d^+ + d^-) \dots\dots\dots (6)$$

The state of the reaction was conveniently followed by use of conductivity probes. A Beckman industrial conductivity transmitter and a dipping probe were calibrated, and the signal was fed to a flat-bed recorder.

The resin batch to be used was first fully converted to the hydrogen form in a fixed bed with 0,5 M sulphuric acid. All the free acid was then washed out of the bed with distilled water. Measured batches of resin were added to the distilled water in the mixer.

When a run was carried out, the mixer was brought up to the speed desired and then sodium hydroxide was added to bring the suspension of resin in the water to an initial pH value of about 11. The recorder trace showed a sharp rise followed by an exponential decay to a constant value over several minutes.

The rate of reaction according to equation (5), if excess hydrogen-form resin is present, can be expressed as

$$-d[Na^+]/dt = K_L A [Na^+] \dots\dots\dots (7)$$

The presence of excess hydrogen-form resin ensures that the concentration of sodium ions at the surface of the resin is negligibly small.

Equation (7) can be integrated to give the form

$$\ln\{[Na^+]_0/[Na^+]\} = K_L A t \dots\dots\dots (8)$$

Each measurement of the reaction rate produced a decay curve on the recorder trace. It was assumed that the conductivity at any time, *t*, as a fraction of the initial peak value was the same as the function  $[Na^+]_0/[Na^+]$ .

Several points from each curve were plotted against time on semi-logarithmic paper to find the value of the constant  $K_L A$ . The value of *A*, the surface of resin beads per unit volume of suspension, was calculated from the volumetric fraction of resin and its mean diameter to give a value of  $K_L$ , the mass transfer coefficient. The

reproducibility of the measurements of these mass transfer coefficients was within about 5 per cent.

*Mass Transfer Coefficients with Activated Carbon*

Measurements of the mass transfer coefficient were made for the adsorption of silver cyanide onto activated carbon. The silver cyanide was taken up from solution in demineralized water, as well as from a 50 per cent slurry of gold-plant residual ore. As before, the depth of water or slurry was equal to the diameter of the tank.

Le Carbone G210 AS activated carbon was used for the tests after it had been screened to produce a fraction between 1,4 and 1,7 mm. The carbon was dried at 110 °C to constant mass. Quantities of 58 g of carbon were measured out and then wetted with distilled water before being added to the mixer. Some properties of the carbon are listed in Table II.

Potassium silver cyanide was used to make up the solution, which was held at a pH value of between 8,0 and 8,5. The initial concentration of silver was about 30 p.p.m. expressed as silver per mass of clear solution. The silver concentration in the mixer was determined from 5 ml samples that had been analysed by atomic-absorption spectrophotometry.

The mixer was run at a speed sufficient to just suspend all the ore particles, except for the small Prochem impeller, which could not achieve this condition and was not used further. These speeds were observed to draw all the floating carbon particles into the slurry.

The mass transfer coefficient was derived from the concentration of silver at various times by the use of equation (8) as described for the ion-exchange resin.

*Attrition of Activated Carbon*

The attrition of activated carbon in clear water was measured, followed by determinations of the proportion of carbon fines in samples taken from the tank at various times. It was not possible to use an ore slurry, since the ore particles would have overlapped the carbon fines in size and would have made such a measurement impossible.

Fresh, dried activated carbon was screened to remove all the fines smaller than 1,0 mm. Batches of this material were used to make up slurries containing 25 and 100 g of carbon per litre of slurry for the attrition tests. The slurries were made up from 58 litres of distilled water and the associated carbon to the same level as in the previous work.

Samples of about 1 litre were drawn after the mixer had operated at set speeds for periods of 5, 12, 24, 36, and 48 hours. These were drawn through a PVC pipe of 32 mm diameter into a vacuum flask. The sampling points were at three different heights in the mixer.

The slurry of carbon in water was filtered to recover all the carbon, which was then dried at 140 °C. The dried carbon was screened at 1,0 mm, and the fines were weighed and expressed as the percentage of the total carbon,  $X_A$ . All the carbon extracted from the sample was returned to the tank as soon as possible so that a constant carbon content was maintained in the slurry.

**Results and Discussion**

*Power Drawn by Prochem Impellers in Clear Water*

The power drawn in clear water at various speeds was

measured for all three sizes of Prochem impeller, as well as for the inclined-blade turbines. In Fig. 5, the power number,  $N_p$ , is shown plotted against the Reynolds number of the mixer for the Prochem impellers. The general shape of the curves is typical of axial-flow impellers, as given by Uhl and Gray<sup>2</sup> and Oldshue<sup>4</sup>.

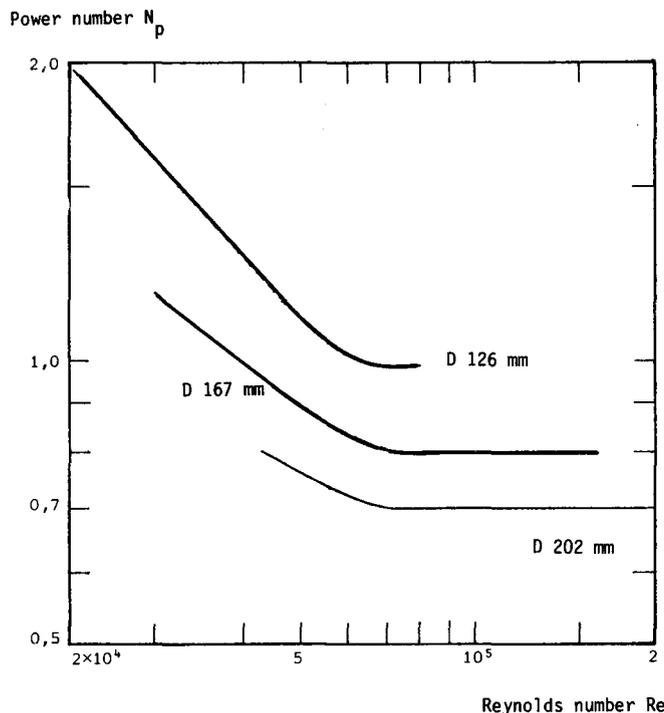


Fig. 5—Correlations of power number against Reynolds number of the mixer for 3 Prochem impellers,  $TIC = 4$  and  $TIZ = 1$

#### Power Required to Just Suspend Solids

The power required to just suspend solids is plotted against the concentration of resin in Fig. 6. Curves for the three sizes of Prochem impeller are shown with one of the turbines for comparison. It is clear from these graphs that the power drawn by the Prochem impellers was only about one-quarter of that drawn by the turbine.

The fact that the intermediate size of Prochem impeller gave the lowest power requirement (Fig. 6) indicates that there is an optimum ratio of tank to impeller diameter. The range of similar impellers available showed only that the optimum value of  $T/D$  was between 2 and 3. This experimental value is supported by Coetzee's deductions<sup>15</sup> from Zwietering's correlation<sup>7</sup> that the optimum value lies between 2,1 and 2,5.

The effect of the clearance between the impeller and the base was studied for two values of clearance,  $C$ , by use of the same tank diameter,  $T$ . Coetzee<sup>15</sup> showed that the smaller clearance,  $T/C = 4$ , gave lower power requirements than the greater clearance,  $T/C = 2$ , for all conditions.

Cloete and Coetzee<sup>6</sup> calculated the theoretical minimum power to just suspend solids,  $P_{min}$ , and compared it with the minimum power actually required,  $P_{JS}$ , for a set of readings (Table III). These values of the power ratio  $P_{JS}/P_{min}$  emphasize the improvement achieved by the Prochem impeller over the action of the turbine.

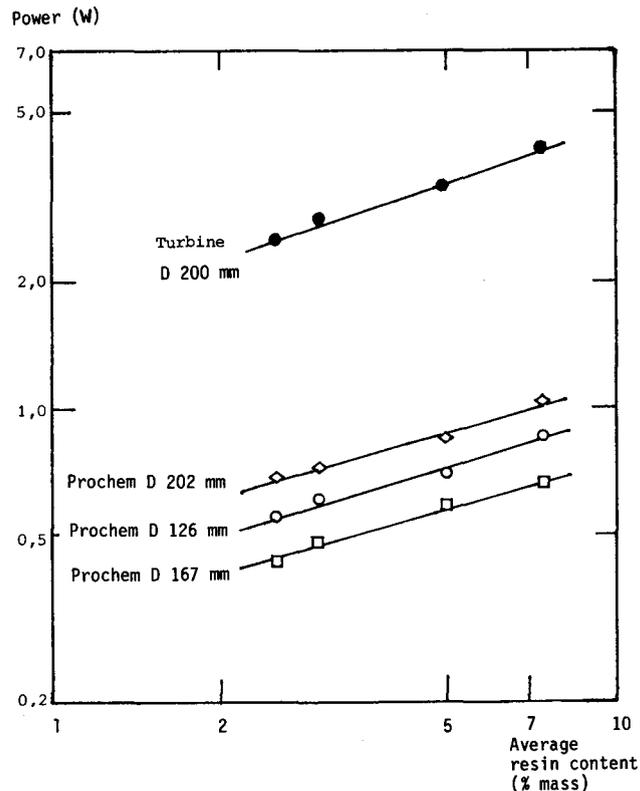


Fig. 6—The effect of the type and size of impeller on the power drawn by the mixer to just suspend the resin in water,  $TIC = 4$

TABLE III  
COMPARISON OF ACTUAL POWER TO JUST SUSPEND SOLIDS WITH THEORETICAL MINIMUM POWER\*

Impeller	Actual power to suspend solids W $P_{JS}$	Power ratio $P_{JS}/P_{min}$
Prochem 167 mm diameter 108 r/min	0,65	76
Prochem 202 mm diameter 96 r/min	1,03	120
Turbine 200 mm diameter 138 r/min	4,17	484

\* The tank shown in Fig. 1 was used for all the measurements. The tank contained 4,36 kg of ion-exchange resin in clear water, with  $T/C = 4$ , giving a total volume of 54,8 litres of slurry. The minimum fluidizing velocity of the resin was 0,94 mm/s. The theoretical minimum power to suspend the batch of resin,  $P_{min}$ , was thus 0,0086 W in all cases—from equation (2).

#### Vertical Concentration Profile of Suspended Solids

The vertical concentration profiles of suspended solids in two experiments using Prochem and turbine impellers of very similar diameter are shown in Fig. 7. The clearance ratio was  $T/C = 2$ , an inefficient value, to illustrate the difference between the flow pattern generated by the two types of impeller. Both impellers were operated at the 'just suspended' condition, which implies that the turbine was rotating about 30 per cent faster than the Prochem.

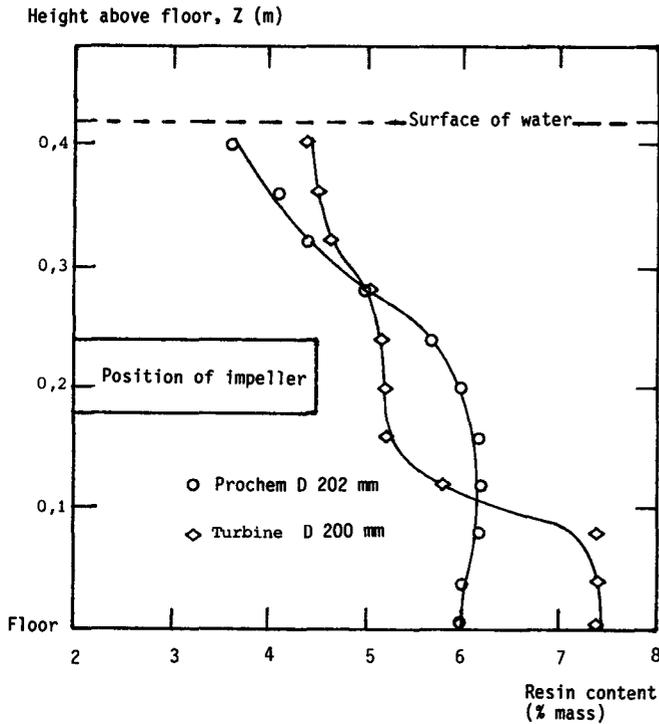


Fig. 7—Vertical concentration profile of the resin in the mixer with 2 different impellers at  $T/C = 2$  at the just-suspended condition

The Prochem impeller generates a much more uniform concentration in the lower half of the tank, leaving a clear zone near the surface. On the other hand, the turbine produces much less axial flow since the concentration near the base is high.

Coetzee<sup>15</sup> also studied the effect of increasing the mixer speed by 60 per cent more than the  $N_{JS}$  value to show that a uniform concentration profile would not be obtained even then. The corresponding power used was increased to 400 per cent of that at the point when the particles were just in suspension.

#### Mass Transfer Rates to Resin Beads

Coetzee's experiments<sup>15</sup> included some to determine the mass transfer coefficient in the liquid film,  $K_L$ , for a turbine of 0,2 m diameter and the set of three Prochem impellers. The speed of the mixers varied from below the minimum for complete suspension,  $N_{JS}$ , to above that speed. Most of the work was done at a low clearance of  $T/C = 4$ , which had been shown to be the most effective. Concentrations of resin were set at three levels: 3, 5, and 7,5 per cent by mass. One set of data was obtained for  $T/C = 2$  for comparison. The power drawn was also measured.

A typical set of results is shown in Fig. 8, in which the mass transfer coefficient is plotted against the power drawn. The salient features are, firstly, the sharp change in slope of the curves at a certain value of power and, secondly, the fact that all the results seem to fall on the same line above the elbow in the curve. All the other sets of measurements exhibited similar characteristics.

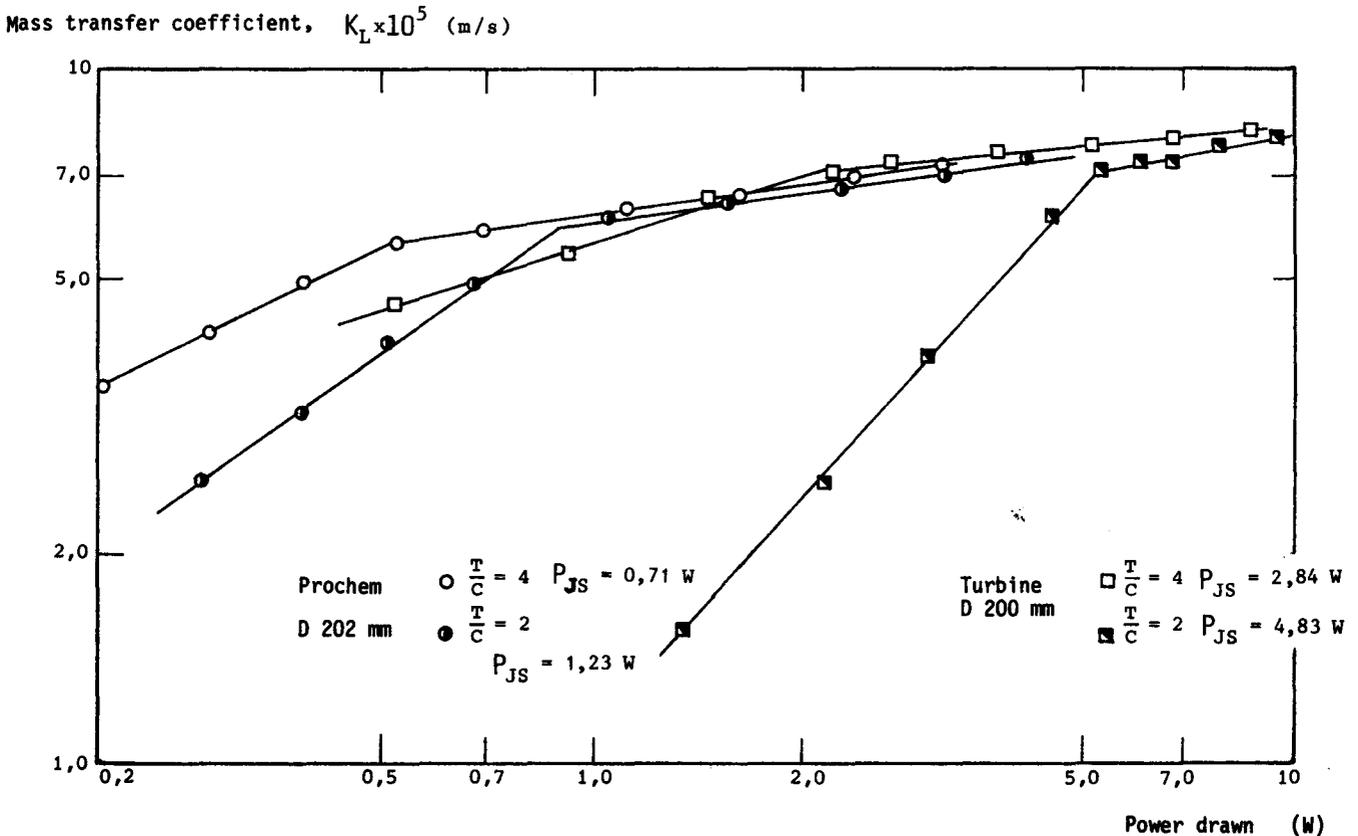


Fig. 8—The effect of the power drawn on the mass transfer coefficient with various impellers and clearances at an average resin content of 3 per cent by mass

The sharp change of slope corresponded to the observed value of  $N_{JS}$  for that system within 10 per cent. The reduced values of  $K_L$  below the elbow in the curve were caused by some of the resin forming a layer on the base. As more resin became suspended as the result of an increase in mixer speed, the average value of  $K_L$  increased sharply until the point of complete suspension was reached, when a further increase in speed had only a relatively slight effect.

The second important point arising from these results was that the value of  $K_L$  at the 'just suspended' condition,  $K_{LJS}$ , was independent of the size, type, or position of the impeller. Coetzee<sup>15</sup> reports that the average value,  $K_{LJS}$ , for all 16 sets of measurements was  $5,33 \times 10^{-5}$  m/s, with a standard deviation of  $0,87 \times 10^{-5}$  m/s. Nienow and Miles<sup>19</sup> and Nienow<sup>13</sup> also draw attention to the constant value of  $K_{LJS}$  obtained for a given system. The value of  $K_{LJS}$  was calculated from the data given in Table II as  $9,3 \times 10^{-5}$  m/s following the approach of Davies<sup>12</sup> and as  $10,2 \times 10^{-5}$  m/s using Nienow's modification<sup>14</sup> of the Frössling equation.

The discrepancy between the calculated values and the average measured by Coetzee is due to the mixture of particle sizes of the ion-exchange resin used in his experiments, whereas the predictions were calculated on the assumption of a strictly uniform particle size. On the other hand, Coetzee's results compare well with the mass transfer coefficients measured in a pulsed fluidized bed by Bennett, Cloete, and Streat<sup>20</sup> using ion-exchange resin of a similar type and size range, which gave a value for  $K_L$  of  $3,8 \times 10^{-5}$  m/s under comparable conditions.

When Coetzee<sup>15</sup> correlated the values of  $K_L$  for fully suspended particles against the power drawn, he obtained 0,167 as the exponent of power. Comparative values ranging from 0,1 to 0,29 for this exponent are reported by Harriott<sup>8</sup>, Sanger and Deckwer<sup>9</sup>, Levins and Glasbury<sup>10</sup>, and Oyama and Endoh<sup>11</sup>.

The effect of resin concentration on  $K_L$  was determined from a comparison of the values at a constant power input of 1,37 W for the Prochem impellers and 4,56 W for the turbine. The resin was fully suspended in all the tests using these power inputs. The results are shown in Fig. 9, where an increase in the average resin concentration in the mixer from 3 to 7,5 per cent decreased  $K_L$  significantly.

This observation supports the theoretical approach of Davies<sup>12</sup>, who allocated a term to account for the local damping effects of solids on  $K_L$ . The experiments reported by Boon-Long *et al.*<sup>21</sup> indicate that the value of  $K_L$  is reduced by the presence of inert particles to the same degree as if they were reacting particles.

#### Mass Transfer Rates to Activated Carbon

The results obtained from measurements of the adsorption rate of silver cyanide onto particles of activated carbon suspended in clear solution and in slurries are summarized in Fig. 10, which was taken from unpublished work by Coetzee.

The fall in the concentration of silver in solution with time for the various impellers was plotted on a log-linear scale. A straight line was obtained only for the first 5 minutes of the reaction. It follows that mass transfer through the liquid is the controlling mechanism only for

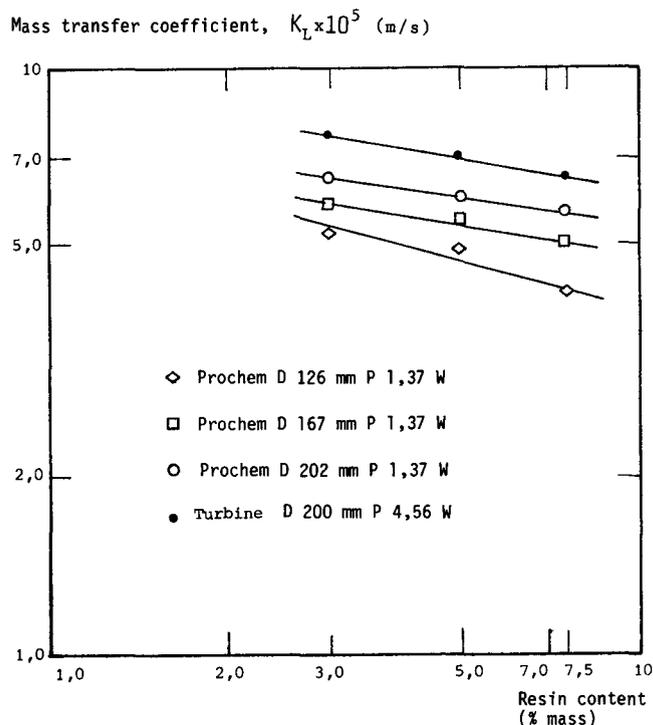


Fig. 9—The effect of the resin content on the mass transfer coefficient at  $T/C = 4$

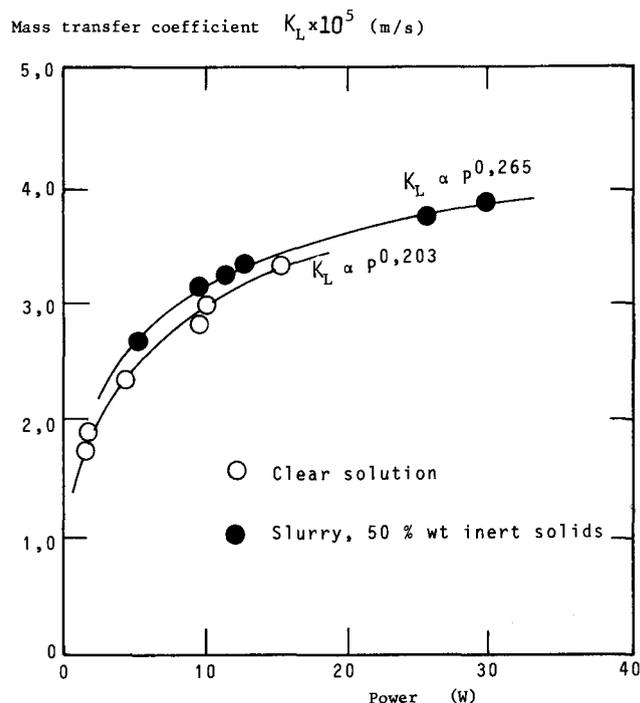


Fig. 10—The effect of the power input on the liquid-film mass transfer coefficient in clear solution and slurry (silver taken up onto activated carbon)

the initial stage of this process.

The initial linear portion of this graph was used in each case in the derivation of a mass transfer coefficient based on the liquid film,  $K_L$ , as for the work using ion-exchange resin. The mass transfer coefficients obtained were not directly comparable with those obtained for the ion-exchange resin since the particles of activated carbon

had a granular shape. The greater density of the carbon could also have an effect.

The results of all the measurements of mass transfer coefficient,  $K_L$ , using activated carbon and either clear solution or slurry were plotted against the power drawn by the impeller shown in Fig. 10. These values were proportional to the power to the exponent 0,203 for clear solution and 0,265 for slurry containing 50 per cent inert ore. This exponent is comparable with the value of 0,167 that was found for spherical ion-exchange resin in this work and the published values ranging from 0,1 to 0,3 mentioned above.

**Rate of Attrition of Activated Carbon**

The typical pattern for the attrition of carbon with time is shown in Fig. 11 for both the Prochem and the turbine impellers. It is evident that the amount of fines increases fairly rapidly during the first 12 hours and much more slowly after that. The decrease in the rate of attrition has been observed in related processes<sup>22-25</sup>, and is probably due to an increase in the attrition resistance of particles as the rough edges are smoothed off and weaker particles are eliminated. Forsythe and Hertwig<sup>22</sup> note that the presence of fines tends to reduce the attrition rate of suspended solids by cushioning the collisions of coarse particles.

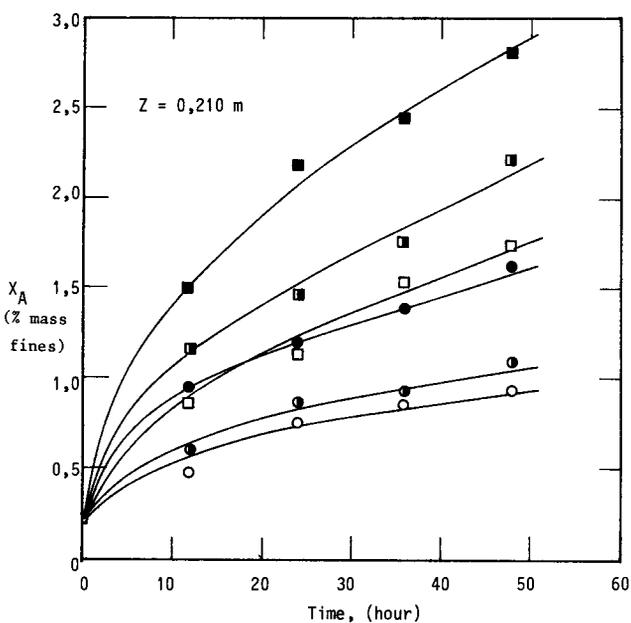


Fig. 11—Increase in the carbon content (smaller than 1,00 mm) with time for the Prochem and turbine impellers, TIC = 2, 25 g of activated carbon per litre

- |                                   |                                     |
|-----------------------------------|-------------------------------------|
| <b>Prochem (diameter 0,202 m)</b> | <b>Turbine (diameter = 0,200 m)</b> |
| ○ P = 1,45 W                      | □ P = 4,91 W                        |
| ● P = 2,40 W                      | ▣ P = 8,21 W                        |
| ● P = 4,49 W                      | ■ P = 15,21 W                       |

The amount of fines generated with time has been shown by Gwyn<sup>26</sup> to be described by an equation of the form

$$X_A = K_2 t^m \dots\dots\dots (9)$$

The values reported for  $m$  were between 0,43 and 0,72

for such disparate systems as cracking catalyst in an air-fluidized bed<sup>22,23</sup> and nickel sulphate crystals in methanol<sup>24</sup>. On the other hand, the value of the constant  $K_2$  is strongly dependent on the actual system and the design of mixer.

Unpublished work by Coetzee has shown that no simple rate equation for the attrition of activated carbon covers the full range of measurements. His equation, equation (10), is a version of equation (9), and correlates the amount of fines produced in terms of the total amount of energy transferred to the suspension by the mixer after the initial conditioning phase.

$$X_A = 0,056 \times E^{0,6} \dots\dots\dots (10)$$

The results of over a hundred measurements are plotted in Fig. 12 for a concentration of 25 g of dried activated carbon per litre of a slurry consisting of carbon in water. These were correlated by equation (10), as shown in Fig. 12.

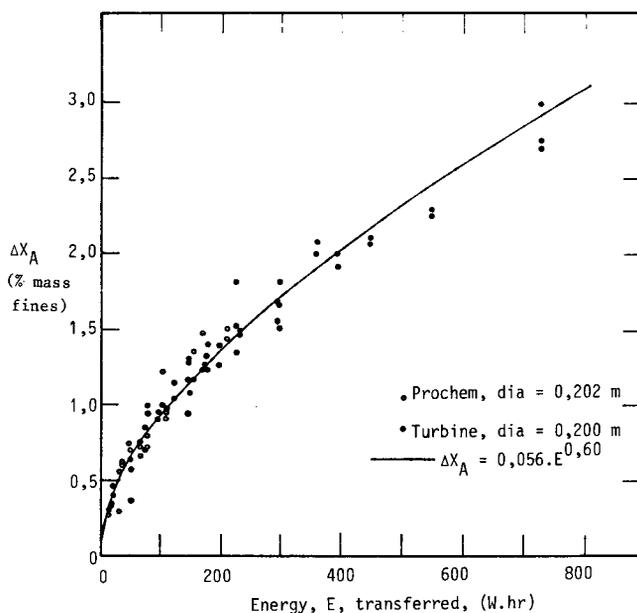


Fig. 12—Variation in the fines content,  $\Delta X_A$ , with the total amount of energy,  $E$ , transferred to 58 litres of a suspension containing 25 g of dried activated carbon per litre

The effect of a fourfold increase in carbon concentration to 100 g/l on the amount of fines produced was also studied. These results could also be correlated by an equation similar to equation (10) with the same exponent of 0,6 for the energy term. The value of the constant was increased from 0,056 to 0,073. Hence, the higher concentration of carbon caused an increase of 30 to 34 per cent in the attrition loss for the same amount of energy absorbed by the slurry.

The effect of an ore slurry on the attrition rate was not studied in this work since the additional experimental effort would not have been justified by the relevance of the results. Further experiments investigating the effect of ore slurries would have to be done in the process evaluation of an actual ore deposit, which was not the case here.

**Comparison of Prochem with Turbine Impellers**

Mixers for carbon-in-pulp processes must suspend all

the particles of ore so that sand does not accumulate in the tanks. They should also be designed to obtain the highest rate of mass transfer to the carbon particles with the lowest loss of carbon due to attrition.

It was shown in the work dealing with mass transfer to ion-exchange resin that the mass transfer rate reached a certain value that was almost independent of the type of mixer *once the solids had been suspended*. Further increases in power beyond that point resulted in only a slight improvement in the rate of mass transfer.

The starting point in the design of a mixer for a carbon-in-pulp application is the determination of the minimum shaft speed and power required for just suspending the coarse solids and activated carbon.

Power in excess of that required to just suspend solids in the mixer in a carbon-in-pulp process will increase the rate of mass transfer only slightly, since the rate was shown to be proportional to the power to an exponent between 0,167 and 0,265. However, the rate of carbon attrition was shown to be more strongly affected by the power; the exponent was 0,6. Improved mixer designs must therefore concentrate on a reduction in the power required as the overriding consideration.

The advantage of the Prochem design of impeller lies primarily in the fourfold reduction in power to just suspend solids. Effective mass transfer is therefore achieved at one-quarter of the power used by the turbine. The attrition loss of activated carbon would thus be only 40 to 50 per cent of that of the equivalent turbine also operating at the point of just suspension.

This study did not extend to other impellers on the market that also create an axial-flow pattern. These include various proprietary designs, as well as the conventional marine propeller. It seems reasonable to expect that all such axial-flow impellers would behave in a similar way to the behaviour exhibited by the Prochem design.

### Conclusions

- (1) The Prochem design was shown to be a better design of impeller for a carbon-in-pulp process than the conventional turbine made up from flat blades inclined at 45 degrees. The primary reason for this is that the Prochem impellers used only about *one-quarter of the power* required for a turbine to fully suspend solids.
- (2) The Prochem impellers produced a stronger axial downflow than the turbine. This was inferred from the vertical profile of the solids concentration.
- (3) The medium-sized Prochem impeller required the least power of the three used to suspend solids. The use of Zwietering's equation showed that the ratio of tank to impeller diameters should lie between 2,1 and 2,5 if the power drawn by the Prochem impellers is to be minimized.
- (4) The sixteen different combinations of impeller type, size, and depth of immersion all gave the same value of mass transfer coefficient *when the charge of ion-exchange resin was just fully suspended*. This was  $5,33 \times 10^{-5}$  m/s, with a standard deviation of  $0,87 \times 10^{-5}$  m/s. Consequently, the Prochem design of impeller achieved the same rate of mass transfer at only one-quarter of the power required by the turbine.

- (5) The mass transfer coefficient to the ion-exchange resin was increased only slightly by a power input in excess of the minimum to just suspend all the solids. An increase in the average concentration of solids from 3 to 7,5 per cent resulted in a noticeable reduction in mass transfer coefficient, which is in accordance with published results.
- (6) The mass transfer coefficients to the activated carbon were slightly more dependent on the power drawn than those measured for the ion-exchange resin. However, mass transfer through the liquid film controlled the overall reaction only for the first 5 minutes, after which resistances inside the particles became significant.
- (7) Rapid attrition of the activated carbon took place during the first 12 hours of mixing in clear water. All the measurements of carbon attrition after the first 12 hours could be correlated in terms of the total energy absorbed by the slurry to the exponent 0,6. This correlation included various sizes of Prochem and turbine impellers and different power inputs. The effect of a fourfold increase in the concentration of activated carbon was a rise of about 30 to 34 per cent in the amount of carbon fines produced for the same energy absorbed.
- (8) The rate of attrition is expected to depend on the type, grind, and density of any ore slurry. No tests were carried out on this aspect since no particular ore deposit was envisaged for the work.
- (9) The power required to just suspend solids appears to be a most important criterion for a mixer to be used in a carbon-in-pulp process. Other impellers designed to produce an axial-flow pattern efficiently should provide the same advantages as impellers of the Prochem design.

### Acknowledgements

The authors thank Edward L. Bateman Ltd for its financial and technical support of the project. One author (MCC) acknowledges bursaries awarded by the CSIR and the Sasol-Stellenbosch 2000 Fund.

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$d_p$	m	Size of particle
$E$	W · h	Energy absorbed by mixer contents
$I/I_0$		Ratio of light intensities
$K_1$		Calibration constant in equation (4)
$K_2$		Calibration constant in equation (9)
$K_L$	m/s	Liquid-film mass transfer coefficient
$K_{LJS}$	m/s	Value of $K_L$ when solids are just suspended
$M_S$	kg	Mass of solids suspended in mixer
$m$		Constant in equation (9)
$N$	1/s	Rotational speed of mixer shaft
$N_{JS}$	1/s	Value of $N$ when solids just suspended
$N_p$	$P/P_H$	Power number of mixer
$P$	W	Power drawn by mixer
$P_H$	W	Theoretical hydraulic power of mixer
$P_{JS}$	W	Power when solids are just suspended
$P_{min}$	W	Theoretical minimum power to suspend solids
$Re$	$ND^2\rho/\mu$	Reynolds number of mixer
$Re_p$	$d_p U_R \rho/\mu$	Reynolds number of particles
$Sc$	$U/\rho d$	Schmidt number
$Sh$	$K_L d_p/d$	Sherwood number
$Sh_{JS}$		Value of $Sh$ when solids are just suspended
$T$	m	Diameter of mixer tank
$t$	s	Elapsed time in a reaction
$U_{mf}$	m/s	Minimum fluidizing velocity of solids
$U_R$	m/s	Notional velocity between solids and liquid
$X_A$	%	Proportion of carbon present as fines
$X_V$	%	Proportion of resin by volume in slurry
$Z$	m	Depth of liquid in mixer
$\mu$	kg/m · s	Dynamic viscosity
$\rho$	kg/m <sup>3</sup>	Density of liquid
$\rho_s$	kg/m <sup>3</sup>	Density of solids
$\Delta\rho$	kg/m <sup>3</sup>	Density difference between solids and liquid

### Nomenclature

Symbol	Unit	Parameter
$A$	m <sup>2</sup>	Surface area of solids in mixer
$C$	m	Clearance between impeller and base
$D$	m	Diameter of mixer impeller
$d$	m <sup>2</sup> /s	Diffusivity of an ion

## Rock mechanics in underground coal mining

The object of the 1989 coal symposium being organized by the eastern Transvaal branch of the South African National Group on Rock Mechanics (SANGORM) is to identify advances made in designing and supporting underground coal-mine workings. Particular emphasis will be placed on the importance of rock-mechanics input to safe and efficient design and operations. The Symposium, 'Advances in Rock Mechanics in Underground Coal Mining', is to be held in Witbank on 7th September, 1989.

The following topics will be discussed:

- Design of pillars
- Multiple-seam workings
- Total extraction

- Support systems and techniques
- Numerical modelling
- Case histories.

All correspondence and enquiries related to the Symposium should be addressed to

Shirley Thorpe  
 The Symposium Secretary  
 SANGORM Coal Symposium 1989  
 P.O. Box 61809  
 Marshalltown  
 2107 South Africa.  
 Telephone: (011) 726-3020.

## Engineering Awards

The winner of the coveted Gold Fields National Engineering Award was announced by Mr Robin Plumbridge, Chairman and Chief Executive Officer of Gold Fields of South Africa Limited, at a recent function.

Mr Michael Seitz, mechanical engineering student at the University of the Witwatersrand, was presented with the first prize of R10 000 for his final-year thesis, 'The generation of shock waves and their interaction with porous plates' and his oral presentation of the thesis.

In addition to walking off with the first prize, Mr Seitz won a grant of R10 000 for his university's Faculty of Engineering, as well as R10 000 for the department in which he was a student. This makes the first prize worth a total of R30 000—Southern Africa's most sought-after academic prize in the field of engineering.

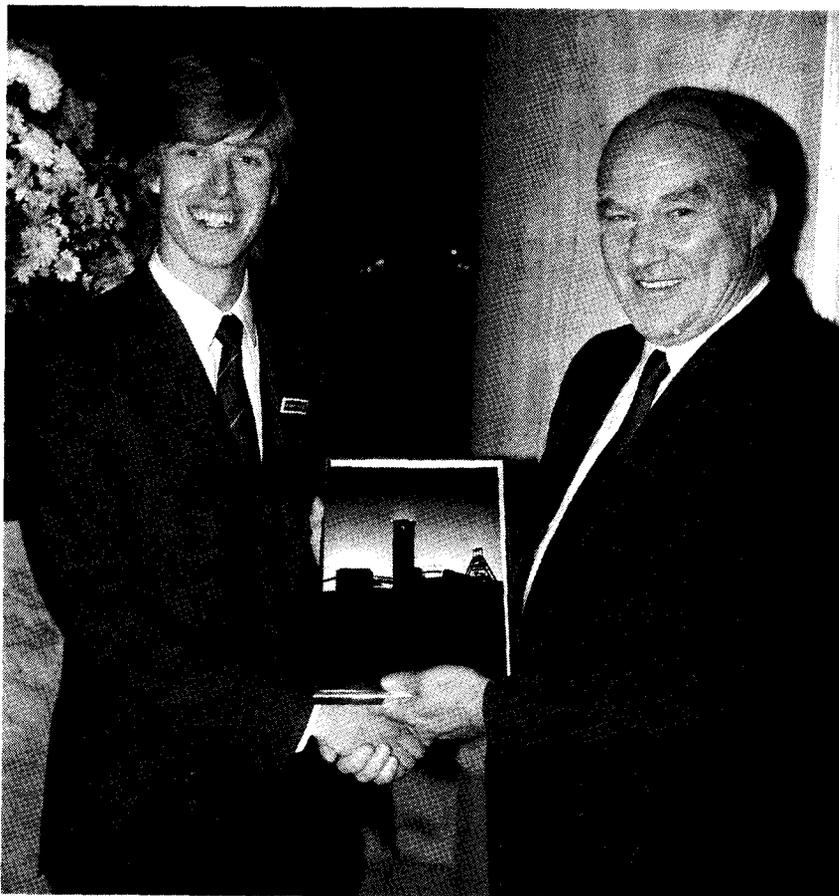
The runner-up, Mr Leon Liebenberg, mechanical engineering at the Rand Afrikaans University, was awarded the sum of R5000 for his thesis 'Die hidrouliese analogie in diep water n.a.v. sleuraspekte van 'n Busemann-dubbelrompboot'.

The remaining five candidates received R1000 each for having been nominated by their universities. Each university affiliated to the South African Federation of University Engineering Students (SAFUES) selected a candidate who, in their opinion, presented the most outstanding design project in his final year during 1988. The awards are made annually in co-operation with the Federated Society of Professional Engineers (FSPE). The candidates

are assessed on written and oral presentations of their theses by judges nominated by Gold Fields. The written theses are judged by engineers of the Gold Fields group in conjunction with an outside examiner, while a separate panel of judges, consisting of outside engineers and Gold Fields officials, adjudicate the oral presentations.

These five candidates are as follows:

<b>N.W. van der Walt</b>	Mechanical Engineering	University of Pretoria
	'Die eksperimentele optimalisasie van 'n lugdinamiese voorwerp vir minimum sleepkrag'	
<b>J.J. Barnes</b>	Mechanical Engineering	University of Cape Town
	'The strength and deformation of pipe sticks'	
<b>M.J. Fourie</b>	Electronic and Electrical Engineering	University of Potchefstroom
	'Energiepulpstelling—stoor en versendeenheid (ETSVE)'	
<b>A.E. Conradie</b>	Mechanical Engineering	University of Stellenbosch
	'Warmlug sirkulasie by droë koeltorings'	
<b>F. Grey</b>	Civil Engineering	University of Natal
	'An investigation into dynamic pressure effects associated with filter sand flowing in a flat-bottomed silo'	



Mr Michael Seitz (left) being congratulated by Mr Robin Plumbridge