The Design of Draft Tube Circulators

By
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ABSTRACT

Draft tube circulators are now widely used instead of Pachucas for suspension of slurries in large tall tanks. Precipitators in the alumina industry are an example.

Draft tube/tank diameter ratio is critical. Two independent criteria are given for optimum ratio. The hydraulic and energy relationships are defined. These require an impeller of very high specific speed. For a stable and efficient system the impeller should have aerofoil blades with a pitch angle which decreases from hub to tip.

The draft tube must be matched to the impeller with inlet baffles above the impeller and flow control vanes below it. Tip recirculation must be suppressed. The tank itself should have a filleted flat bottom.

Such a system exhibits the behaviour of axial flow devices with the characteristic undesirable behaviour at low flow. Installed and operating power requirements depend critically on hydraulic design and to a lesser extent on speed reducer fficiency.

The problems of re-suspension have been overcome by a patented slot system which also improves behaviour at low flow to permit a more economic design. A number of other practical operating considerations are also discussed.

Keywords: *Agitators, air-lift agitators, draft tube circulators, mechanical agitators, leaching, mineral processing, Pachucas, precipitators.*

INTRODUCTION

This paper deals with the hydraulic and energy considerations in the design of draft tube circulators. Although it is based largely on experience with alumina, the concepts have since been applied successfully in a wide range of other applications.

Agitation of slurries in deep tanks is a common requirement in mineral processing and in some chemical plants. For many years the traditional approach was to use air lift agitators, commonly known as Pachucas (Fig. 1). Conventionally a Pachuca tank (Lamont, 1958) has a 90° or 60° conical bottom and a height/diameter ratio of 2.5 or 3. The air lift tube is around 10 per cent of tank diameter. Air injection produces flow of slurry up the tube at quite high velocities.

Pachuca systems are expensive when the cost of cone bottom tanks, compressors and piping is taken into account. Pachucas require a high energy input for a given level of agitation because most of the considerable kinetic energy in the draft tube flow is dissipated as local turbulence in the upper part of the tank.

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Alumina

In earlier years, apart from uranium and gold leaching, a classical application of Pachucas was in the alumina industry for the precipitation step of the Bayer process. But as alumina plants increased in size, these tanks became quite large, 10 or 12 m diameter and up to 40 m high. The costs of cone bottom construction, compressors and piping escalated, as did power costs and the cost of removing the severe scale deposits which formed in Pachucas with some bauxites.

About 20 or more years ago the alumina industry started investigating the alternative of mechanical draft tube circulators in locations as diverse as Europe, the Virgin Islands and Taiwan, but with indifferent success. Then, in the mid 1960's, when the Queensland Alumina Limited plant at Gladstone was being planned, the design of an effective mechanical circulation system was studied in detail. The original Gladstone plant had 30 mechanically agitated precipitators each 11 m diameter and around 30 m high. This was a large enough installation to justify such an exercise. As far as is known, this was the first major alumina facility in the world designed with mechanical circulators. The concept worked well although the configuration used was not optimum and there were some lessons to be learned for the design of future plants.

Since then the concept has been developed and refined from the point of view of both process and mechanical design. Now in the alumina industry alone, this type of mechanical circulator is fitted to some 450 tanks ranging from 3 to 14 m diameter, in 14 different plants and 8 different countries. The same technology, or derivations of it, is also being applied in a wide range of other applications including gold leaching, crystallizers for the fertilizer industry and draft tube aeration for wastewater treatment.

Conditions which point to the application of mechanical circulators include

1. slurries in large tanks especially tanks with a high height/diameter ratio,
2. series operations in which all tanks operate full,
3. situations where it is essential to minimize energy use for agitation and
4. applications requiring control of shear and velocity gradients.

Generally mechanical circulators are not suitable for tanks in which liquid level varies or where height/diameter ratio is around unity. Open impeller agitation is better in these situations.

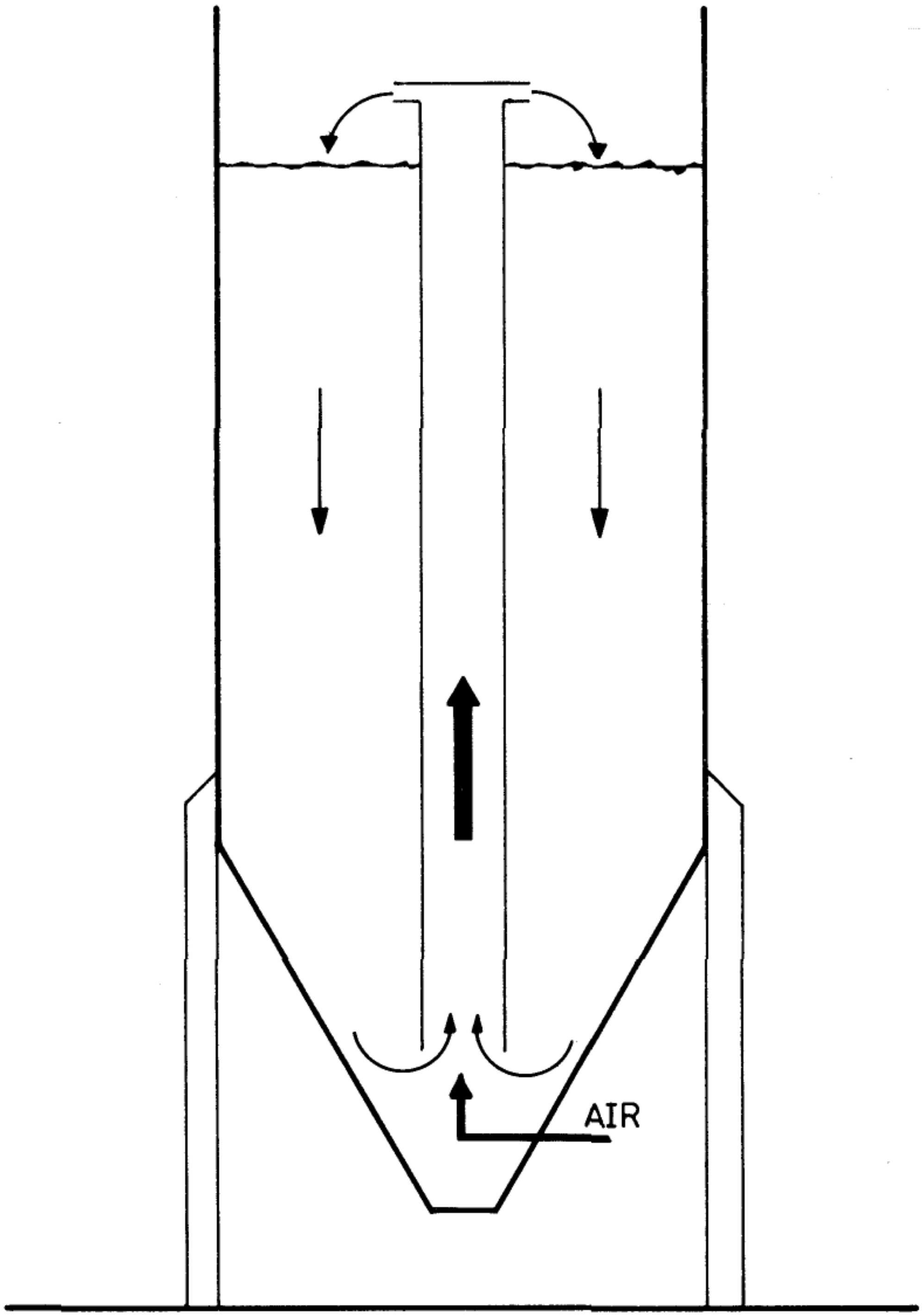


FIG. 1—Pachuca tank.

DESIGN CONSIDERATIONS

In broadest terms a draft tube circulator consists of an essentially flat-bottomed tank containing a draft tube which, in practice, will be in the range of 20 to 40 per cent of tank diameter. Near the top of the draft tube is an axial flow impeller which pumps down the tube producing a return flow up the annulus (Fig. 2).

Except in very special applications an up-pumping impeller is inappropriate because, as in the Pachuca, the kinetic energy would be dissipated instead of doing useful work. *It is better to pump down so that the "jet"* from the draft tube continually sweeps the bottom of the tank clean and moves particles out to the annulus region where they are carried to the top of the tank.

Velocity criteria

There are two distinct velocity criteria which must be considered.

1. The velocity down the draft tube, irrespective of draft tube diameter, is set by the bottom sweeping requirement. This must be determined experimentally. It is a function of particle size distribution, per cent solids, rheology of the pulp and bottom shape.

2. Independently, there is the minimum average upward velocity in the annulus. This is a multiple of the free settling velocity (FSV) of the largest particle to be circulated. But this multiple must be large enough to prevent progressive accumulation of large particles in the annulus. This phenomenon is called "teeter". It develops exponentially, sometimes over a period of days, and can result in a complete loss of circulation. In some cases the situation can be complicated by the further growth of crystals suspended in the annulus.

The draft tube/tank diameter ratio at which these *velocities are both satisfied is the point at which power* requirements are minimized (Fig. 3). This has proved to be a very valuable design concept which has resulted in a 35 per cent reduction in the power required to do the same agitation job.

Flow/head/power relationships

Nomenclature

T = Tank diameter (m)	K = Head loss coefficient
D = Draft tube diameter (m)	η = Hydraulic efficiency
V = Velocity (m/s)	ϱ = Specific gravity of slurry
A = Area (m^2)	Subscripts:
Q = Flow (m^3/s)	$_t$ = Tank
H = Head (m)	$_d$ = Tube
P = Power (kW)	$_a$ = Annulus
X = D/T	$_h$ = Hydraulic
N = rev/min.	$_m$ = Motor

Flow and head

$$Q_d = 0.785\ V_d\ T^2\ X^2 \quad m^3/s$$

$$Q_a = 0.785\ V_a\ T^2\ (1\text{-}X^2) \quad m^3/s$$

But in actual operation $Q_d = Q_a$ so we have:

$$V_d = V_a \frac{1\text{-}X^2}{X^2} \quad \text{and thus } X = \sqrt{\frac{V_a}{V_a + V_d}}$$

At the velocities and geometries applying, fluid friction is a negligible factor. Head requirements relate almost entirely to draft tube inlet and outlet losses, reversal losses at the tank bottom and acceleration of fluid to draft tube velocity. Thus total head loss is a multiple of draft tube velocity head. The coefficient is a function of draft tube design.

$$H = 0.0510\ KV_d^2$$

Power requirements

The total hydraulic power required to produce circulation is given by

$$P_h = 9.794\ QH\varrho \ = 0.499\ KQ\ V_d^2\varrho \ = 0.392\ KD^3\ V_d^3\varrho$$

Note that power is proportional to the cube of the draft tube velocity, so it is essential that great care be taken in the experimental determination of the minimum draft tube velocity.

Hydraulic and mechanical efficiency

Actual power input to the impeller will equal the required hydraulic power divided by the hydraulic efficiency of the impeller. Impeller efficiency may vary from 30 to 40 per cent for a simple flat plate impeller running in a plain draft tube to 70 per cent for a complex aerofoil blade impeller running in a properly designed draft tube. Impeller efficiency can have a major impact on the energy economies of the system.

The drive motor power input required will equal the impeller power input divided by speed reducer efficiency. With a right angle spiral bevel reducer or a parallel shaft reducer efficiency at the partly loaded conditions is likely to be 95 per cent. (Fully loaded efficiencies will be as high as 97 per cent.) A worm type reducer will have an efficiency of only 75 per cent for these speeds and loadings.

Optimum D/T ratio

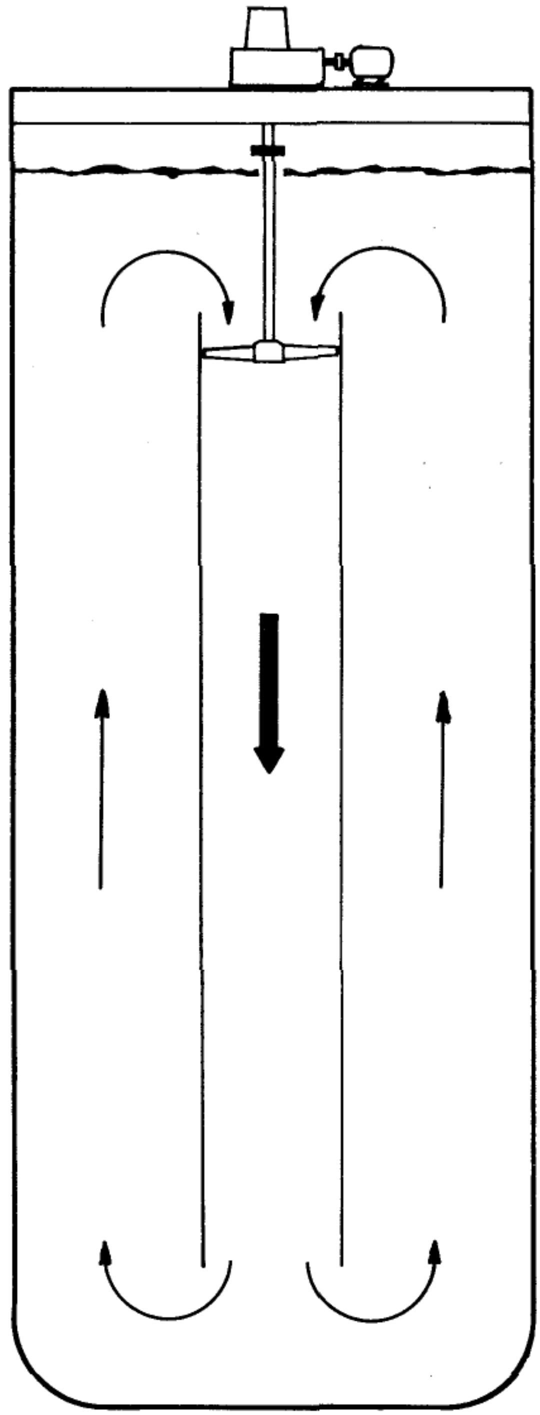
From the above equations one can determine the effect of D/T ratio (X) on the power needed to produce either the minimum required draft tube velocity or the minimum required annulus velocity. It can be shown that

at constant draft tube velocity, $P \propto X^2$

at constant annulus velocity, $P \propto \frac{(1 - X^2)^3}{X^4}$

These curves are plotted on Fig. 3. At the point of intersection of these curves both velocity criteria are satisfied but the power requirement is at a minimum. However, because of the relative steepness of the left hand curve, it is better to err on the high side for D/T in case of doubt.

The application of these design considerations to a specific case is given in the Appendix.



DRAFT TUBE CIRCULATOR

FIG. 2—Draft tube circulator.

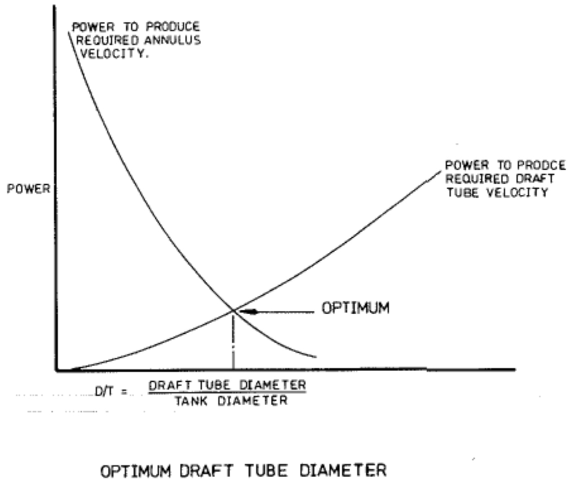


FIG. 3—Optimum draft tube diameter.

IMPELLER-DRAFT TUBE BEHAVIOUR

An impeller-draft tube system exhibits the same sort of behaviour as an axial flow pump. The hydraulic characteristics are important. Hydraulic efficiency and power-flow relationships determine operating energy requirements; the form of the head vs flow curve determines the stability of the system and its capacity to recover after a process upset. These characteristics depend critically on the design of the impeller and draft tube and the proper matching of these components. This can be illustrated by comparing the behaviour extremes of a primitive system (A) and a very sophisticated system (B). Practical systems may lie midway.

System A has a 30° or 45°, 4-bladed, flat plate axial flow turbine (or two of them) running in a plain cylindrical draft tube (Fig. 4).

System B has an impeller with blades of a specific aerofoil section with a progressive increase in pitch angle from hub to tip (Figs. 5 and 6). The draft tube has an exponential, flared entrance, inlet baffles, some way of suppressing recirculation around the impeller tip and a stator vane and diffusor assembly below the impeller.

Power characteristics

In all draft tube systems at low flow, hydraulic efficiency falls off sharply and the power absorbed by the impeller increases. At zero flow, or "shut-off", the power absorbed can be twice the power at the design operating flow and even more with primitive impellers (Fig. 7).

Shut-off power dictates the size of the drive motor and the size of the speed reducer. In normal operation both the motor and speed reducer may be running at substantially less than rated capacity. This effect tends to be more marked for type A systems.

Developments discussed later have substantially reduced this problem and led to more cost effective designs.

Head and flow characteristics

The head vs flow (or "pump") curve of any axial flow device has a characteristic discontinuity at intermediate flows and also an unstable region at low flows. The discontinuity corresponds to the stall point of the impeller blade; as flow decreases, the perceived angle of attack of the relative velocity vector increases until boundary layer separation occurs.

System A has a fairly flat curve with the discontinuity at a relatively high flow. But System B has a steeper curve and the discontinuity is displaced to a fairly low flow (Fig. 8). (This is because the aerofoil section has more tolerance to increase in the perceived angle of attack.)

The actual operating point is the intersection of the "pump" curve with the "head loss" curve. But the head loss curve may be steeper during a process upset due, for example, to partial blockage of the draft tube outlet.

The combination of a type A curve and a severe process upset can give an intersection in the discontinuity region from which the system is unable to recover (Fig. 9). In contrast the type B system is capable of operating stably over a wide range of process conditions.

Draft tube design

A typical type B draft tube is shown in Figs. 10 and 11. This incorporates a number of important features.

1. The draft tube entrance is constructed from a series of conical frustra with a lip of rolled pipe. This construction is an economic approach to the theoretical exponential flare with a 2:1 area ratio. Four flat vertical baffles control swirl.
2. Recirculation around the impeller tip is suppressed by a patented 'notch' (Watson, 1973). This greatly improves hydraulic efficiency without the need for a close clearance impeller or a steady bearing to locate it.
3. The impeller reacts with curved stator vanes and a central diffuser cone located just below the impeller. The resultant draft tube flow is quite uniformly distributed with a negligible rotational component.
4. A limit ring below the impeller, mounted on the top of the diffuser cone, limits radial movement of the impeller due to random fluid forces.

Economic considerations

The type B system is more expensive to construct but is usually justified on large installations by energy savings. More recently, designs have been evolved for special axial flow impellers which are less expensive to build but of intermediate efficiency. These can be the economic optimum for small tanks, intermittent operation or applications requiring a low hydraulic energy input.

Tank bottom design

Overall, the most effective arrangement is a flat bottom tank with filleted corners. The draft tube terminates

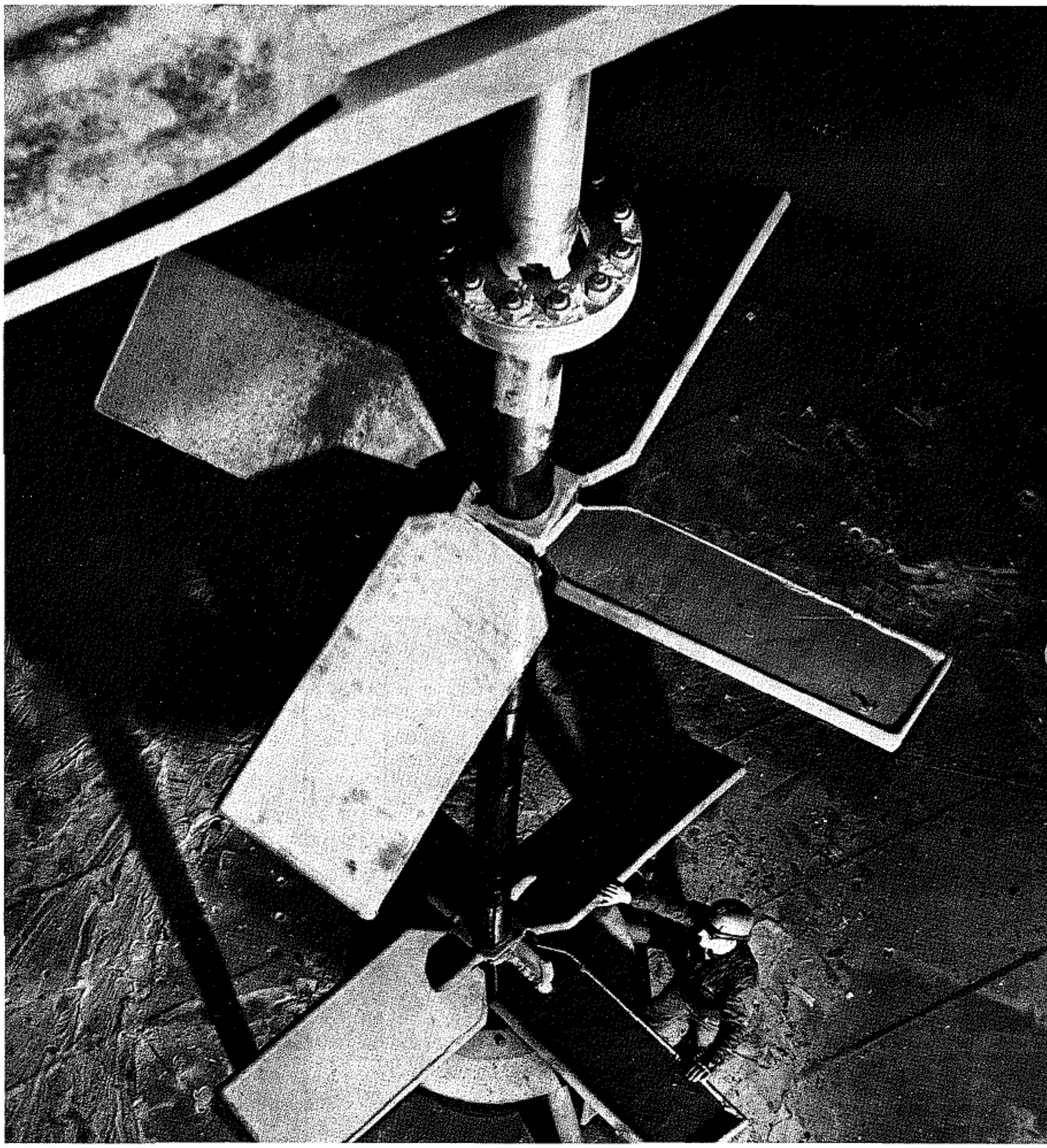


FIG. 4—Dual 30° flat blade axial flow turbine.

about one diameter above the bottom. More elaborate configurations appear to offer little advantage.

Fillets should be used. In an unfilleted tank, deposits tend to build up in a random manner which produces asymmetrical distribution of the flow. Even with fillets, some solids deposition may occur but this is non-progressive and reaches equilibrium quickly.

Fillet construction is not critical. Some alternatives are shown on Fig. 12. The unstressed flat fillet is simplest if fill cost can be tolerated.

Filleted flat bottoms and the relatively quiescent top surface of a mechanically circulated tank compared with a Pachuca allow a 20 to 30 per cent operating volume increase for the same total tank height. Usually the savings in tank cost more than cover the cost of fabrication of the draft tube.

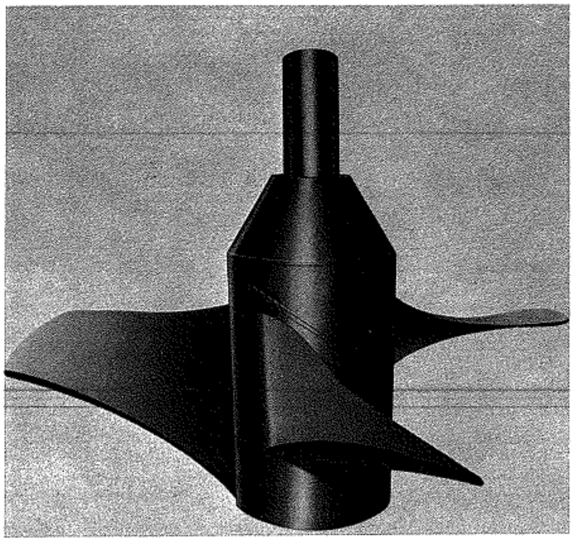


FIG. 5—Complex aerofoil impeller (cast construction).

RESUSPENSION AND START-UP

General

After a power failure, or before initial start-up, settled solids can completely block off the end of the draft tube. Whether or not the shut-off head of the system is sufficient to displace this plug without external aids will depend on the shear-viscosity-flow relationships of the settled solids.

The relative difficulty of resuspension and the cost of designing for the high power demand under shut-off conditions were a problem with early designs.

Resuspension vents

Around 1970 a modification (Landberg, 1970) was patented to deal with the problems of resuspension and high power at shut-off. A series of slots or "resuspension vents" were made in the draft tube extending to some distance above the calculated level of completely settled solids (Fig. 13). Under shut-off conditions the flow bypasses through these slots at a relatively high velocity and progressively erodes and suspends the settled solids. In quite large tanks resuspension can be completed within an hour or so, provided solids have not agglomerated.

Under normal operating conditions, bypass through the slots has been measured at less than 10 per cent. This is no problem and indeed it gives a desirable progressive increase in annular velocity toward the top of the tank.

Effect on system characteristics

The slots have a significant effect on the form of the head vs flow and power vs flow curves for the system. When the end of the tube is blocked off, slot bypass means a zero flow condition is never reached. The net effect is to chop off the unstable low flow region of the H vs Q curve and give a system which is completely stable over the whole operating range (Fig. 14).

A similar effect is observed on power usage. With slots, power usage peaks at only 25 to 30 per cent above normal operating power and this enables smaller motors and smaller speed reducers to be used for the same process conditions (Fig. 14).

MOTOR AND POWER REQUIREMENTS

Operating power

The hydraulic power is proportional to the draft tube head loss coefficient. The operating power is inversely proportional to the efficiencies of the impeller and the speed reducer. Each of these may vary over a wide range depending on the design of the draft tube, impeller and speed reducer.

1. Draft tube head loss coefficient may vary between 1.35 and 2.
2. Impeller efficiency may vary between 40 per cent and 70 per cent.
3. Reducer efficiency may vary between 75 per cent and 95 per cent.

Using the most favourable of these figures (which are already being achieved in several hundred installations), the operating power in the example calculates as

$$\frac{19.3 \times 1.35}{0.70 \times 0.95} = 39 \text{ kW}$$

But the primitive impeller running in a plain cylindrical draft and driven by a worm speed reducer could well require an operating power which is greater by a factor of $\frac{2}{1.35} \times \frac{70}{40} \times \frac{95}{75} =$ approximately 3.

Installed motor power

The installed motor should be sized for shut-off power plus a 10 to 15 per cent factor to cover variations in specific gravity and other random effects.

Shut-off power is 2.0 times operating power for a plain draft tube and 1.25 to 1.3 times operating power for a slotted draft tube.

Thus for the type B system the installed motor (and speed reducer rating) is 56 kW (instal 75 HP) if the draft tube has slots. If the draft tube does not have slots, the installed motor rating would be 86 kW (instal 125 HP). The speed reducer should have a corresponding rating.

For the more primitive type A design the required horsepowers would become quite uneconomic for the application used in the example and even a system of intermediate efficiency would be unacceptable.

Plant example

The application of the principles outlined can be illustrated by comparing two actual installations both in tanks 11 m diameter and operating on a slurry of the same specific gravity and particle size distribution.

One installation has a 2.75 m draft tube, without slots. The circulator driver has a 125 HP motor which

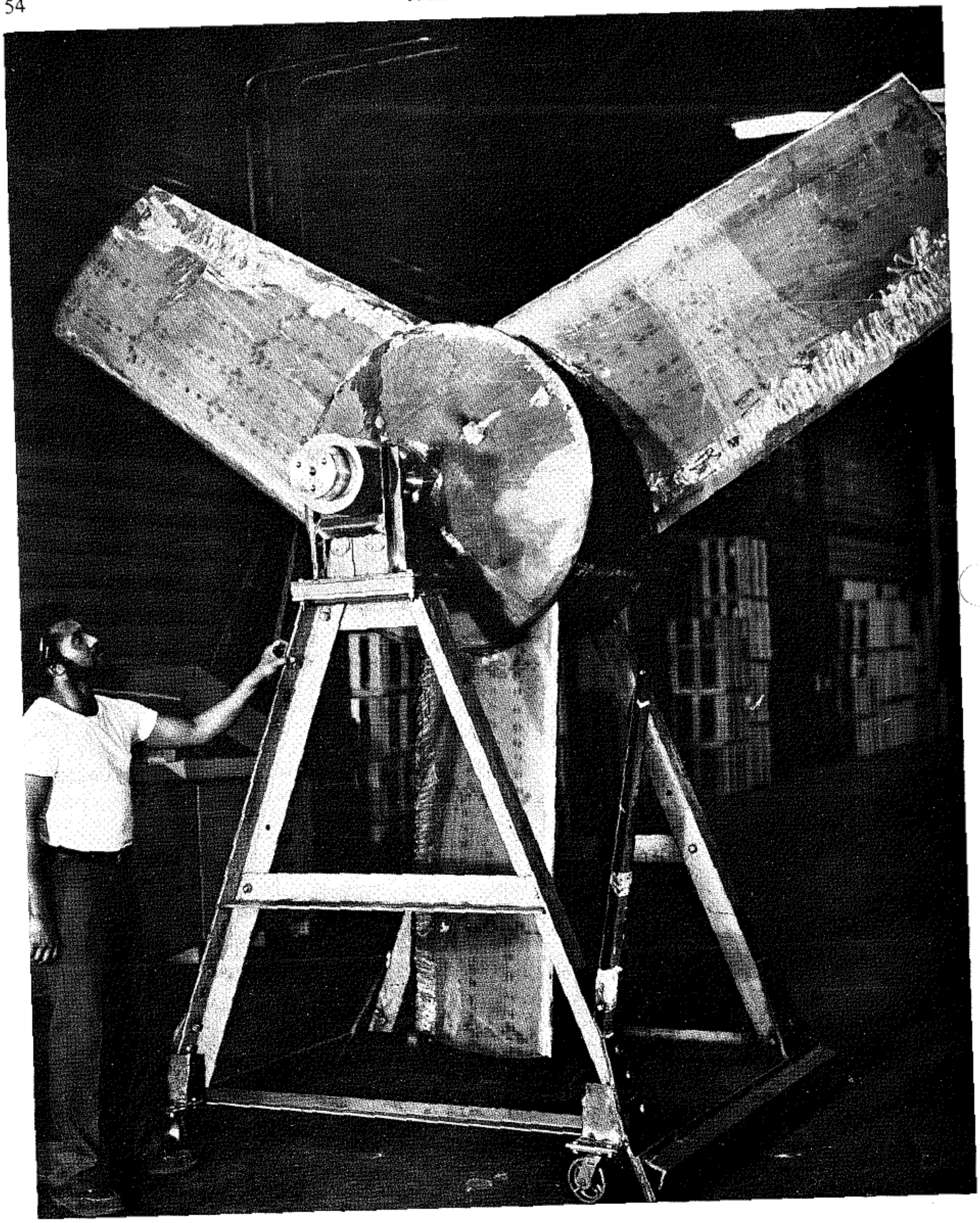


FIG. 6 – Complex aerofoil impeller (fabricated construction).

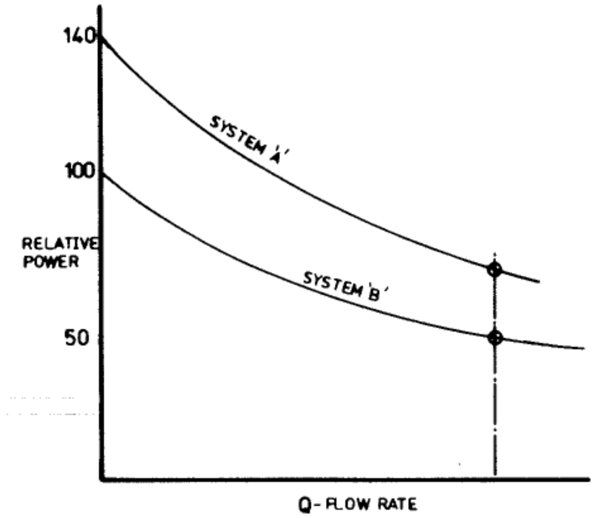


FIG. 7—Power versus flow.

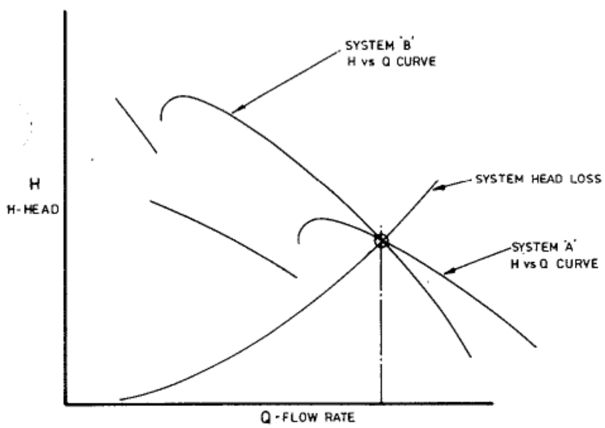


FIG. 8—Impeller comparison.

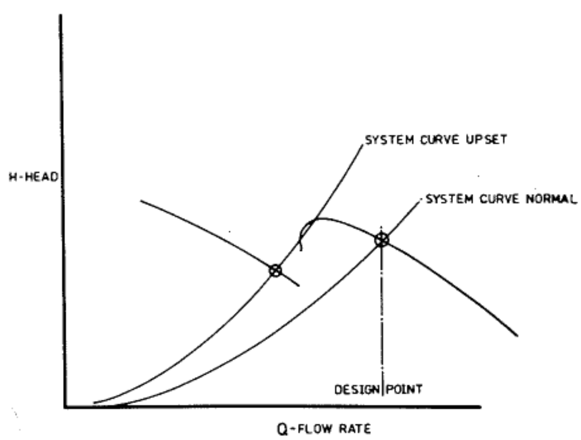


FIG. 9—System "A" impeller operating points.

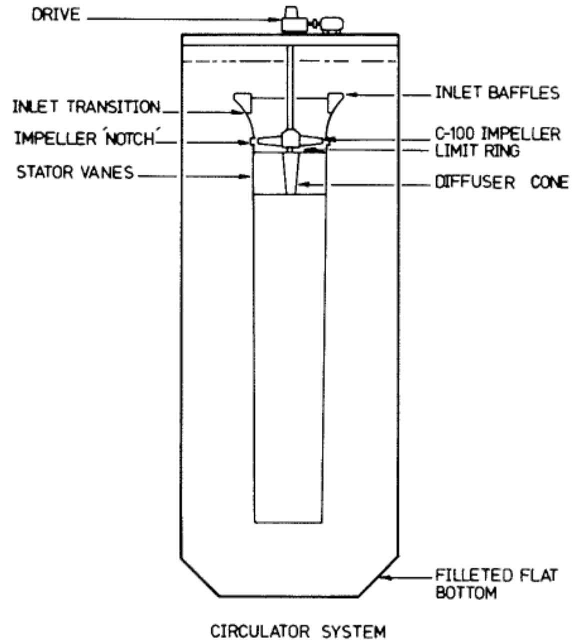


FIG. 10—Circulator system.

loads fully at start up and requires 67 HP in normal operation.

The other installation has a 3.35 m draft tube (optimum) with slots. The installed motor is 60 HP. It loads to around 56 HP on start up and requires 44 to 45 HP in normal operation.

Process performance of the two installations is comparable, but circulator first cost and power costs are significantly less for the second. There is a slight increase in cost for the larger draft tube.

OPERATING EXPERIENCE

General

The following comments relate principally to experience obtained in the alumina industry in Australia and overseas.

Impeller wear

Erosion of impeller blades does occur after a few years, mainly in the outer 10 per cent of the blade. This can be repaired in situ or in the shop by various techniques ranging from deposition of weld metal to complete replacement of the blade tip. Recent impeller designs use removable blades to facilitate in-shop repair.

In a given slurry, tip speed has a big effect on blade wear. Accuracy of blade profile and pitching also seems to be a major factor. It is more difficult to maintain accurate blade profile with wear resistant materials as high hardness materials are difficult to form. Rubber covering destroys profile in the important trailing edge region. Sprayed coatings can induce thermal distortion. Overall, the advantages of these materials are doubtful.

FIG. 11—Draft tube notch, stator vanes and diffuser cone.

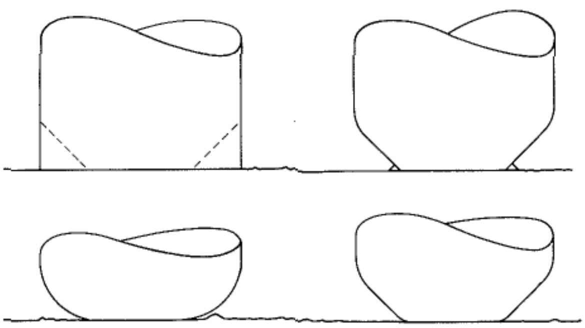


FIG. 12—Fillet construction.

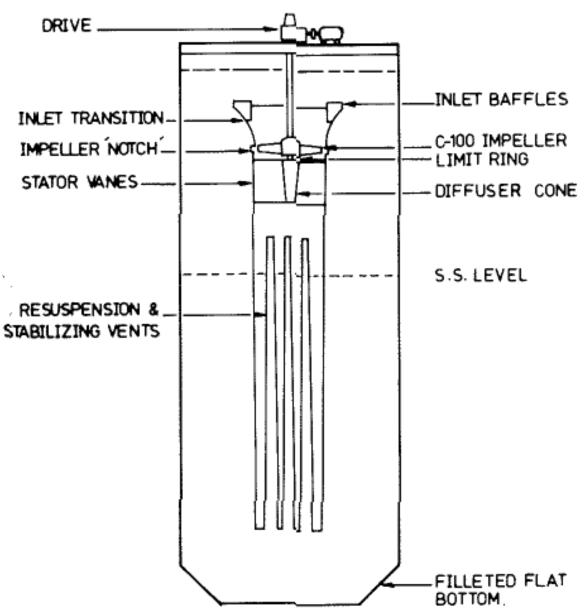


FIG. 13—Circulator system with slots.

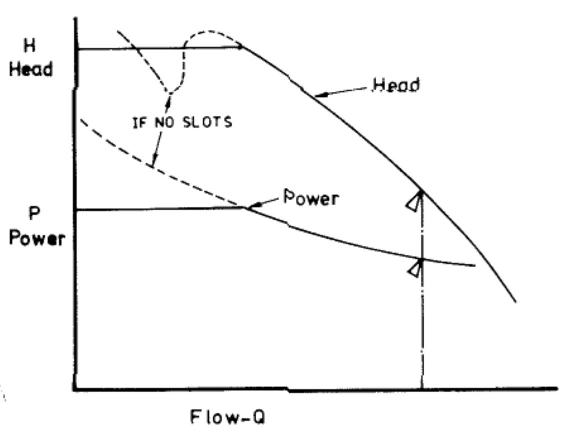


FIG. 14—Effect of slot bypass on head and power.

Provided there is no corrosion problem, the economic solution appears to be to manufacture impellers from mild steel, make them with great care, but use bolted blade construction to facilitate changing and repair.

Many materials of construction have been used for system B impellers. Earlier cast impellers were made of ductile iron, cast steel, Ni-Resist D2 and Ni-Resist D4. Fabricated system B impellers have been constructed of mild steel, stainless steel and exotic alloys including examples over 4 m diameter of Hastelloy G.

Draft tube collapse

There have been several cases of collapse of an unslotted draft tube due to improper operating procedures. For example, an attempt to dilute concentrated caustic soda solution created a situation in which a draft tube containing caustic soda was balanced by an annulus of water. The differential head at the caustic soda level caused failure of the draft tube.

Resuspension phenomena

An attempt to re-start a circulator with a slotted draft tube a short time after a power failure may be unsuccessful. If solids have not settled to slot level, an attempt to start will partially fill the draft tube with supernatant liquor of specific gravity less than that of the average slurry in the annulus. In this "hydraulic stall" situation, the system behaves as if there were no slots and draws full shut-off power.

The solution is to wait for the slurry to settle below the slots, or provide supplementary air agitation in the annulus to feed slurry into the draft tube rather than supernatant liquor.

Draft tube cover

If the liquid level over the draft tube is more than needed, a supernatant layer will develop in which no useful work is done. If the level falls too low, there will be a head loss across the entrance lip which imposes a static head differential on the system and circulation will fall, allowing deposition of larger solids. These may agglomerate causing permanent partial obstruction of the draft tube and permanent loss of circulation.

All episodes of low level should be checked to ensure that any solids deposited have been resuspended.

Intertank connections

Care should be taken to prevent short circuiting. Incoming flow should enter at a point where it will all be carried down the draft tube, but not into the tube itself lest it distort the flow or give hydraulic imbalance on the impeller.

The exit flow should leave through a riser pipe with its inlet well down in the annulus. Some designers run this riser close to the tank bottom to ensure that large solids are removed but this can introduce a head loss penalty, especially with scale build-up in the riser.

Generally velocities should be high enough to carry out all particles (10 to 20 × FSV) but not so high as to require very large differences in level between tanks.

APPENDIX

DESIGN EXAMPLE

Requirements

Consider a tank 7.5 m diameter with a slurry of specific gravity 1.50. The required minimum draft tube velocity (established experimentally) is 1.80 m/s and the required minimum annulus velocity (a multiple of the free settling velocity of the largest particle) is 0.20 m/s.

Optimum D/T is at

$$X = \sqrt{\frac{0.20}{0.20+1.80}} = 0.316, \text{ hence } D = 2.37 \text{ m}$$

$$Q = 0.785\ V_d\ D^2 = 7.95\ m^3/s$$

$$H = 0.0510\ KV_d^2 = 0.165\ K\ m$$

$$P_h = 9.794\ QHP = 19.3K\ kW$$

For simple draft tube designs the value of K is probably in the range 1.7 to 2.0. In practice it has been possible to reduce this to about 1.35 by careful design of the inlet region, internal baffling and correct tank bottom shape. In this example the required hydraulic power with slurry is in the range of approximately 26 to 38 kW depending on tube design.

Impeller efficiency may vary between 40 per cent and 70 per cent depending on the design used. Speed reducer efficiency range is 75 per cent to 95 per cent.

In summary then, the example requires a circulator with an impeller around 2.4 m diameter which pumps 8 m^3/s, develops a head of less than 0.2 m. Hydraulic power will be around 30 kW. Power absorbed will be between 40 and 120 kW depending on the efficiency of the impeller and drive.

Impeller arrangement

One may infer approximate impeller speed from practical design considerations.

This impeller is approximately 2.4 m diameter and irrespective of construction details will have a substantial mass. To prevent vortices, minimum impeller submergence will be approximately 1.5 diameters, and allowing for tank freeboard, mounting beam depth etc. the impeller shaft will be at least 4.5 m long. A submerged steady bearing is unacceptable in a mineral slurry so the shaft and impeller must be designed as a fully overhung system. In practice, critical speed and bending moment considerations set the maximum operating speed to below 100 rev./min. On the other hand, drive costs and certain impeller design considerations point to a speed of no less than 30-35 rev./min. Tip speed constraints can also limit rotational speed.

Specific speed

The flow, head and rotational speed of all fluid pumping devices can be characterized by the ratio, specific speed (N_s).

With the appropriate form and units, specific speed is a dimensionless ratio but it is frequently expressed in the non-dimensionless form

$$N_s = 52 \times \frac{N\ Q^{1/2}}{H^{3/4}} \quad \text{where } N = \text{rev./min.},\ Q = m^3/s,\ H = m$$

Typical values in these units are

1. Centrifugal pump 500 to 2 000,
2. Axial flow pump 3 000 to 5 000, and
3. Kaplan turbine 10 000 to 15 000.

But the head, flow and probable speed requirements in the example correspond to a specific speed of approximately 37 000 which is around three times that of any axial flow device previously designed! Deviation from *this requirement would carry severe energy or initial cost* penalties.

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Landberg, G. G., 1970. Draft tube arrangement, Australian Pat. 438,697.