The Characteristics of a Vertical Submersible Slurry Pump in Transporting Dredged Slurry

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ABSTRACT

The performance of vertical centrifugal slurry pump is quite different from clear water pump due to presence of solid particles in water. An approach to derive the performance behaviour of a vertical centrifugal pump used for transporting dredged slurry based on detail hydraulic loss analysis has been presented in this paper. The derived analytical data has been compared with experimental results. Performance analysis of a vertical submersible centrifugal slurry pump has been accomplished in two stages. At first, performance characteristics of the centrifugal pump with clear water have been investigated considering an in-depth hydraulic loss analysis. Depending on the particle size distribution, the effect of solid particles on the performance characteristics of centrifugal slurry pump has been investigated considering volume fraction of particle size. The homogenous slurry with fine particles has been treated as Newtonian fluid with slurry viscosity and specific gravity. Additional hydraulic losses due to coarse solid particle have been considered for coarse slurry fraction. The performance of the vertical centrifugal slurry pump has been predicted with the accuracies of about 87% and 90 % for respective solid concentration of 18% and 10% by volume near the maximum efficiency point. The drooping performance characteristics at low flow operation have been found deteriorating further with the increase of solid concentration.

Keywords – Centrifugal, Diffuser, Impeller, Slurry

I. INTRODUCTION

Centrifugal slurry pumps are mostly found in transporting solid grains with carrier fluid through the pipe lines to the destined point in the process industries like cement plant, petrochemical plants and fertilizer plants, etc. Performance characteristics of any centrifugal pump significantly differ in the presence of solid particles in the fluid from clear fluid characteristics. The slurry of uniform particle size is hardly found in industries, rather in most of the application particle size varies from few microns to the order of mm. The performance characteristics of the centrifugal slurry pump depends on particle size, size distribution, shape, solid concentration, solid specific gravity, pump speed and certainly on the pump geometry. The presence of solid particles, specifically coarse particles, in the fluid always breaks fluid continuum. The bigger the particle size worse is the effect. In most of the slurry pumping system, particle size distribution is uneven, i.e., it is mixed with fine, medium and coarse particles and it is called heterogeneous slurry.

Previous researchers like Sellgren [1], Gahlot, *et al.* [2] and many other eminent researchers developed empirical formulae correlating head reduction ratio (R_H) with solid concentration by weight, solid specific gravity and particle size. Performance prediction utilizing empirical correlation carried out by them with the error band of ±12% to ±20 % for the test slurry.

$$R_H = 1 - \frac{\text{Pump head with slurry, } H_s}{\text{Pump head with water, } H_w} \tag{1}$$

The present work has been conducted with the objective of detail analysis of several hydraulic losses occurring in the pump. The fine slurry has been considered as Newtonian fluid. The same hydraulic analysis method has been adopted for the fine slurry with the slurry viscosity and specific gravity as presented for the centrifugal pump handling clear water. Additional hydraulic head losses due to the presence of coarse solid particles have been deducted from the fine Newtonian slurry head by applying the approach as postulated by Roco, *et al*. [3]. The prediction of the performance characteristics of the centrifugal slurry pump has been improved by considering the volume fraction of the solid particles.

II. Test Rig & Experimentation

The pilot seabed mining was carried out from an anchor barge near the Kalvadevi bay of Ratnagiri, Maharashtra, India. The seabed mining was carried out by a dredge head with water jets. The dredge head as shown in "Fig. 1" contains a water distributor (1) which provides pressurized water to a series of nozzles (2) housed in an agitating chamber (3). The pressurized water is supplied through feed line (4) and distributed to the nozzles.

Water jets from the nozzles cut the seabed resulting formation of slurry in the dredge head. The solid concentration in the dredge head is varied by controlling the nozzle jet velocity.

The test rig of the seabed dredging system is as shown in "Fig.-2" .The dredge head (1) is suspended from a crane (2) and placed on seabed. The horizontal centrifugal pump (3) mounted on the equipment barge (4) sucks sea water through flexible hose (5) and discharges high pressure water through delivery pipe (6) to the dredge head(1).

The pressurized water released from a set of nozzle cuts seabed resulting formation of solid-water slurry in the agitation chamber of the dredge head (1).The vertical submersible slurry pump (7) mounted on the dredge head (1) sucks slurry from the dredge head and delivers through discharge flexible hose (9) and slurry pipe to the hopper barge (8). A by pass line (10) with flow control valve (11) regulates the pressurised water supply to the dredge head without disturbing the performance characteristics of the water supply pump(3). Power to the equipment is supplied by 320 kVA Diesel Generator Set mounted on the equipment barge.

Data Acquisition System for recording online data in computer has been installed. Magnetic flow meter (14), pressure transmitter (15), and ultrasonic solid concentration meter (16) mounted on slurry pipe line. Pressure transmitter (17) & magnetic flow meter (18) are installed on the clear water pipe line (6). Signal conditioner circuitry converts signal sensed by the respective transducer in to electrical signal which is transferred to a master controller via RS 485 communication port. Master controllers transmit Data to a personal computer via RS 232 –C port for on line display and recording in the hard disk. The investigated pump is single stage centrifugal impeller and diffuser type casing. The details of the pump and characteristics of sea water and sea bed sand are listed in Table- 1

III. Performance Characteristics with Clear Water

III.1 Eulers Head

The energy imparted to the pumping fluid per unit weight of the fluid with infinite number of blades is popularly known as Euler's pump head.

$$H_{th\infty} = \frac{u_2 c_{\theta 2} - u_1 c_{\theta 1}}{g} \qquad (2)$$

Considering zero inlet pre-rotation of fluid in the design.

$$H_{th\infty} = \frac{u_2 c_{\theta 2}}{g} \qquad (3)$$

Table -1

Pump Details	
Rated Capacity	240 m3/hr
Head	25 m
Capacity Range	75 – 400 m3/hr
Motor Power	35 HP
Speed	2,900 rpm
No. of stage	single
No of vanes in impeller	4
Impeller blade inlet angle	18^o
Impeller blade outlet angle	22.5^o
Impeller diameter	198 mm
No. of vane in diffuser	8
Water Properties	
Pumping water	Sea water
Temperature	0 – 20 °C
Specific gravity of clear sea water	1.028 – 1.034
Kinematic viscosity (m^2/s)	$1.83x10^{-6}$ to $1.05x10^{-6}$
Solid Properties	
Type	Seabed sand
Specific gravity	2.7 to 3.5
Particle size (mm)	0.035 to 0.350

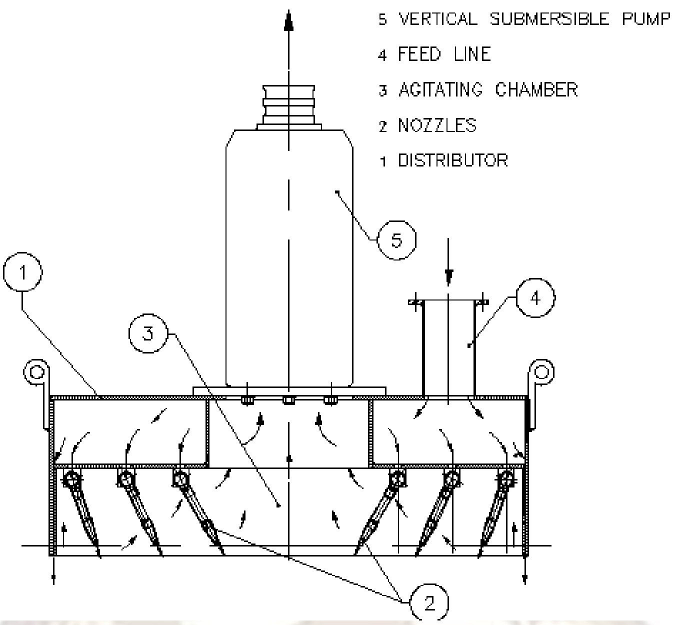

Fig 1 Dredge Head

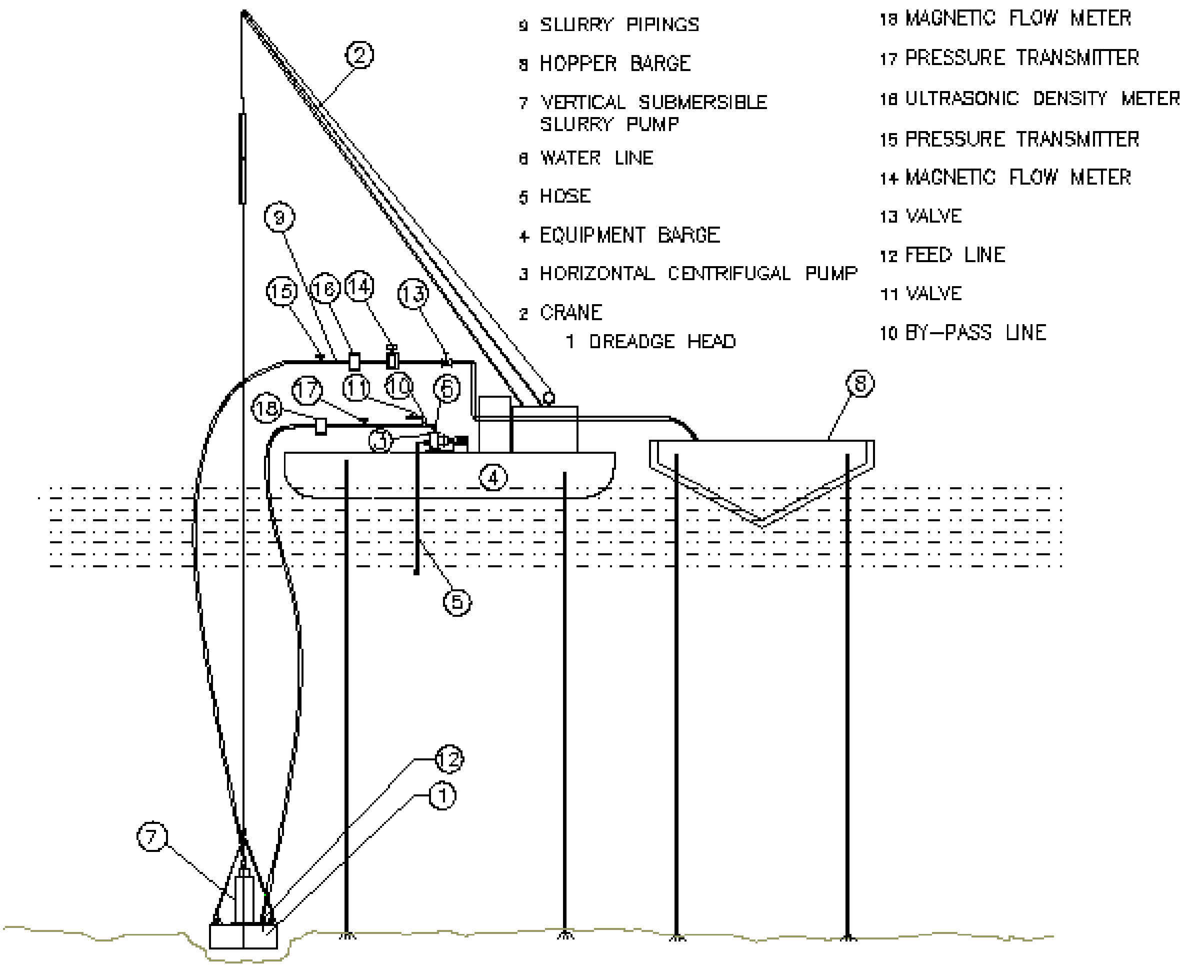

Fig 2 Test Rig

III.2 Slip

Fluid rotates in the reverse direction of impeller rotation at the impeller speed after entering into the rotating impeller from stationery condition. Thus, a reverse circulation is set-up in blade to blade flow passages. These relative eddies at the outer edge of the impeller will have circumferential velocity ($c_{\theta s}$) in the opposite direction of the outlet whirl velocity ($c_{\Theta 2}$) and is known as slip velocity ($c_{\theta s}$)

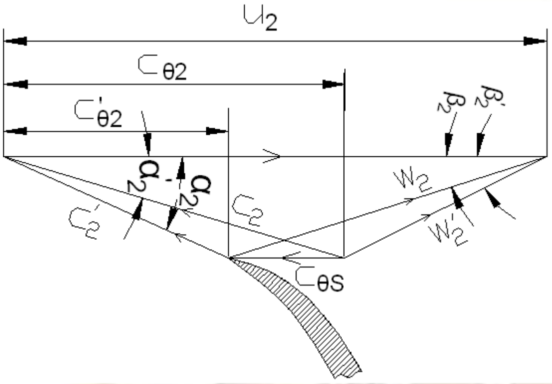

Fig. 3. Outlet effective velocity triangle with slip velocity

It is depicted in "Fig. 3". It has been studied by many researchers that Weisner's[4] slip model gives realistic slip factor and same has been considered for the present work.

$$\sigma_f = 1 - \frac{c_{\theta s}}{u_2}$$

$$\sigma_f = 1 - \frac{\sqrt{\sin\beta_2}}{z^{0.7}} \qquad (4)$$

$$H_{th\infty} = \frac{u_2(c_{\theta 2} - c_{\theta s})}{g} \qquad (5)$$

III.3 Hydraulic losses in the impeller

The fluid while passing through the impeller or diffuser flow passages encounters several hydraulic losses which reduces the effective head developed by the pump. Roco et al [6] classified the hydraulic losses as local hydraulic losses, secondary hydraulic losses and frictional losses. The optimum hydraulic loss model has been considered in the present study which is shown in Table-2.

III.4 Diffuser Losses

Hydraulic losses in the diffuser are calculated in the similar manner as impeller but a stationary frame of reference is considered.

Table. 2 Hydraulic losses

Local Hydraulic Losses	
Shock Losses, Conrad et al. [5]	$h_{inc} = k_{inc}\dfrac{w_{\theta i}^{2}}{2g}$, k_{inc} = 0.5 to 0.7
Mixing Losses, Johnston *et al.* [6], Mizuki *et al.* [7]	$\dfrac{h_{mix}}{\dfrac{\rho c_i^2}{2g}} = \dfrac{1}{1+\bar{\alpha}_i}\left[1 - \dfrac{(1-\varepsilon_{wake})}{(1-\varepsilon_{wake})}\right]$ (6) $\bar{\alpha}_i = \dfrac{c_{\theta 2}}{c_{m2}}$ (7) $\varepsilon_{wake} = 1 - \dfrac{1}{0.45}\dfrac{w_2}{w_{max}}$
Secondary Hydraulic Losses	
Blade Loading Losses, Galvas [8]	$h_{bl} = 0.05 D_f^{\,2}\dfrac{u_2^{\,2}}{2g}$ (8) $D_f = 0.3 + \dfrac{0.75 H_{th1}}{\dfrac{w_1}{u_2}\dfrac{z}{\pi}\left(1-\dfrac{D_1}{D_2}\right) + 2\dfrac{D_1}{D_2}}$ $H_{th1} = \dfrac{u_2 c_{\theta 2}}{u_2^{\,2}}$
Friction	
Skin Friction, Musgrave [9]	$h_f = \dfrac{1}{2} w_m^{\,2}\lambda\dfrac{L}{d_h}$ (10) $\dfrac{1}{\sqrt{\lambda}} = 2\log_{10}\left[\dfrac{w_m d_{hm}}{\upsilon}\sqrt{\lambda}\right] - 0.8$
Clearance Flow	
Clearance losses, Augier [10]	$q_{cl} = zsLu_{cl}$ (1 $u_{cl} = 0.816\sqrt{\Delta P_{cl}/\rho}$ $\Delta P_{cl} = \dfrac{\rho Q[r_2 c_{\theta 2} - r_1 c_{\theta 1}]}{z\bar{r}\bar{b}}$ $\bar{r} = (r_1 + r_2)/2 \qquad \bar{b} = (b_1 + b_2)/2$

IV. Property of Homogeneous Solid Liquid Mixture:

It has been experimented that particles of size below 70 μm remains suspended homogenously in water. Viscosity of such fine solid liquid homogeneous mixture has been calculated using Thoma's [11] correlation and mixture specific gravity as listed below.

$$\mu_m = \mu_w\left[1 + 2.5C_v^{\;2} + 10.5C_v^{\;2}\right] \qquad (12)$$

$$\rho_m = \frac{100}{\dfrac{C_w}{\rho_s} + \dfrac{(100 - C_w)}{\rho_w}} \qquad (13)$$

V. Effects Of Solids on Pump Performance

The centrifugal pump behaves in a quite different manner in presence of solid particles in the pumping fluid. Solid particles can slip from the carrier fluid, i.e., the particles move at a slower or a faster velocity than the carrier fluid or it can move with same velocity as carrier fluid depending on the particle size, particle specific gravity and solid concentration.

Roco, et al. [6] considered the additional head losses due to presence of solid particles in the fluid. They classified the hydraulic losses in three classes, viz., local losses, secondary losses and frictional losses. The additional hydraulic losses due to the presence of solid particles have been estimated by correlation with three non-dimensional numbers namely, particle Reynolds number, Froude number and pump specific speed. It has been observed that the solid particle sizes below 70 μm remain homogenously suspended in the fluid and such particles are treated as fine particles. Homogenous slurry of fine particles in which particles are evenly distributed behaves like a clear continuum liquid and it can well be treated as Newtonian fluid with its specific gravity and viscosity. Coarse particles (70 to 350 μm) are unevenly distributed in the fine homogeneous slurry. The analysis has been done considering coarse particle mean size, d50 = 250 μm and that of the fine particles are of 50 μm. The hydraulic losses have been estimated considering two volume fraction of particles as described above. In brief, hydraulic losses occurred in the pump flow passage are caused by fine homogenous slurry fraction and the additional losses by the coarse slurry fraction. Hydraulic losses (HL) for centrifugal slurry pump are analysed as below.

$$\sum HL_{total} = \sum HL_f + \sum \Delta HL_{sl} \qquad (14)$$

$$\frac{(\Delta H_{sf})_{sl}}{(H_{sf})_f} = 297C_v(\rho_s - 1)\frac{\mathrm{Re}_{sl}}{N_s} \qquad (15)$$

$$\frac{(\Delta H_{loc})_{sl}}{(H_{loc})_f} = \frac{10.8C_v(\rho_s - 1)}{Fr_{sl}} \qquad (16)$$

$$\mathrm{Re}_{sl} = \frac{w(a, c_v)d_p}{\nu}$$

$$Fr_{sl} = \frac{v_*^{\;2}}{ad_p(\rho_s - 1)}\frac{1}{\rho_{sl}}$$

Where, $a = \dfrac{c_{\theta 2}^{\;2}}{r_2}$,

$$v_* = \frac{c'_\theta}{5.98 + 5.75\log_{10}\left[\dfrac{b_2}{2k_{imp}}\right]}$$

$$W(a, C_v) = W_o\left(\frac{a}{g}\right)^{0.5}(1 - C_v)^E$$

The value of E is taken from E vs. Particle Reynolds Numbers curve as given by Gandhi, *et al.* [12]

$$\frac{(\Delta H_f)_{sl}}{(H_f)_f} = 1100Cw(\rho_s - 1)\frac{gd_p}{c^2}\frac{Wo}{c} \qquad (17)$$

VI. Experimental Uncertainty.

Table. 2 Uncertainty of the instrument

Instruments	Make	% of Error
Magnetic Flow Meter	Manas Microsystems Pvt Ltd, India	0.75%
Pressure Transmitter	WIKA Instruments India Pvt. Ltd	0.50%
Ultrasonic Solid Concentration meter	Rhosonics Analytical BV, Netherland	0.10%

VII Results and Discussion

The performance test of a vertical submersible slurry pump has been accomplished with 18 % and 10 % solid concentration by volume and same has been done analytically. It has been observed that analytical performance curve matches very closely to experimental curve at the best efficiency point (bep) (254 m^3/ hr.) with the accuracy of about 87% and 90% for solid concentration by volume (C_v) of 18% and 10% respectively. The present experimentation has been conducted from minimum to maximum flow rate with clear water as well as with slurry by opening the discharge valve gradually. It has been observed that the predicted and the experimental performance curve intersect at some flow rate towards the left of the best efficiency point and these curves closely match in the region from bep to intersection point. As the pump flow reduces from bep operating conditions or in other words the flow velocity reduces, hydraulic head losses as well as the additional head losses due to solid particles decreases although the pump fluid flow remains in the turbulent region (Re ~ 6 x 10^5) with least friction factor. So, in the region from bep to intersection point, predicted performance curves closely match with the experimental curves. It is indicated in Fig.2 and Fig.3. It is also found that from intersection point to the end of the curve, head of the predicted performance curve is higher than the experimental curve for slurry application. The predicted heads are 24% and 15% higher than the experimental heads at the flow rate of 300 m^3/ hr. for C_v of 18% and 10% respectively. The excessive additional head losses due to the presence of coarse solid particles at high flow region may cause this deviation, which could not be captured accurately in the presented analytical technique.

A drooping (stall) performance characteristics in both the experimental and the predicted performance curves have also been observed at an operating point in the reduced flow region. It happens due to steep divergence in blade to blade flow passages. Fluid moves against the positive pressure gradient which thickens the boundary layer and finally it separates from the impeller wall surfaces. Eddy formation takes place in the separated region which causes huge hydraulic losses and it is further deteriorated due to presence of solid particles. The pump again tries to develop higher head to match with the discharge pressure which further increases hydraulic losses. As a result, the head developed by the pump again falls and the pump operation at this flow rate is unstable.

These unsteady flow fluctuation propagates throughout the impeller and diffuser flow passages and the pump experiences stall. Pump performance at this low flow region is also found to deteriorate further with the increase of solid concentration, i.e., it is more prominent when the pump handles slurry of solid concentration by volume 18% than that of 10%. The dotted lines in Fig. 2 and Fig. 3 show the expected performance curves at reduced flow rate while the experimental curves deviate from it.

I: Experimented with clear water
II: Predicted with clear water
III: Predicted with seabed sand slurry
(Conc. 18% by volume)
IV :Tested with seabed sand slurry
(Conc. 18% by volume)

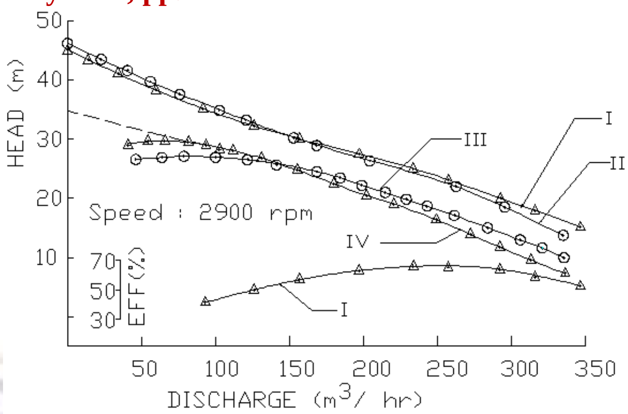

Fig. 3. Performance Curve (18% solid Conc.)

I: Experimented with clear water
II: Predicted with clear water
III: Predicted with seabed sand slurry
(Conc. 10% by volume)
IV :Tested with seabed sand slurry
(Conc. 10% by volume)

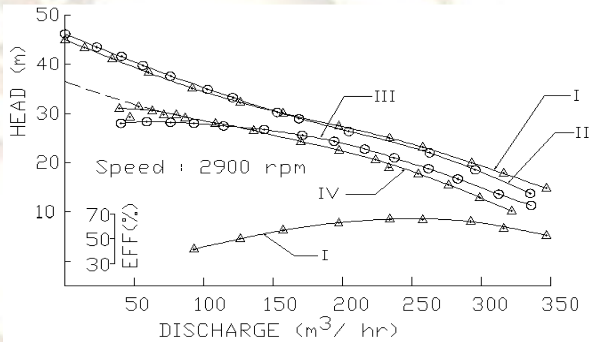

Fig. 4. Performance Curve (10% solid Conc.)

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VIII. Conclusion

Analysis of performance characteristics of centrifugal slurry pumps considering the volume fractions of solid particle depending on particle size and particle distribution gives improved results than considering a mean particle size. The presented method gives reasonably accurate results around the best efficiency point. However, further research, in-depth study and experimentation is really needed for performance analysis of centrifugal slurry pump when it handles highly coarse slurry with varied particle size.

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Nomenclature

a	characteristics local acceleration (m/s²)
bep	best efficiency point
b	impeller width (m)
C_v	concentration of solids in the slurry by volume in decimal fraction
C_w	concentration of solids in the slurry by weight (%)
c	velocity of flow (m/s)
d_p	solid particle size (m)
d_{50}	particle size, 50% by weight passing through the sieve
d_{hm}	hydraulic mean diameter (m)
D	impeller diameter (m)
D_f	diffusion factor
Fr	Froude number
s	clearance gap width (m)
ρ	specific gravity
v_*	friction velocity (m/s)
c'_θ	corrected whirl velocity (m/s)
w	relative velocity (m/s)
Wo	unhindered particle settling velocity (m/s)
W(a,Cv)	modified particle settling velocity(m/s) at local acceleration (a) and solid concentration(Cv)
z	no of vanes
g	gravitational acceleration(m/s^2)
u	impeller peripheral speed (m/s)
h_{inc}	incidence head losses (m)
h_{mix}	mixing head losses (m)
h_{bl}	blade loading losses (m)
h_f	frictional head loss (m)
L	blade mean streamline meridional length (m)
k_{inc}	incidence loss coefficient
k_{imp}	impeller flow coefficient
Ns	pump specific speed (SI)
Δp_{cl}	clearance pressure loss (N/m^2)
Q	pump flow rate (m^3/s)
Q	flow rate (m^3/s)
r	impeller radius (m)
Re	Reynolds number
β	blade angle
λ	friction coefficient
ε_{wake}	width of wake (dimension less)
ν	kinematic viscosity (m^2/s)

Subscripts

1	impeller inlet	f	fluid, fine slurry
2	impeller outlet	s	slip, solid
ϴ		sl	slurry
cl		sf	secondary flow

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