COMMUNICATIONS TO THE EDITOR

Minimum Power Requirements for Slurry Transport

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The suspension of slurries in conduits is of growing importance in such diverse areas as the transport of solids in pipelines and the development of slurry-fueled nuclear reactors. Such applications require the prediction of the minimum conditions under which slurry transport can be accomplished successfully.

Minimum transport conditions have been defined by several previous investigators (*5, 11, 12*) as those conditions under which a stationary layer of particles is first deposited at the bottom of the conduit. The early correlations of these conditions (*5, 11*) predicted the fluid velocity at which stationary particles first appeared (the drop-out velocity). More recently Thomas (*12, 13*) has proposed a correlation predicting the wall shear velocity $\sqrt{g_c \tau_w / \rho_l}$ at which dropout occurs.

Weisman and Efferding have previously studied the suspension of slurries by mechanical mixers (*14*). It was found that at a constant geometry the dispersion of the slurries throughout the mixing vessel was controlled by the dimensionless groups $(g_c P / g \rho_m V u_o)\ (1-\epsilon)^{-2/3}$. The suspension of all particles from the vessel bottom was found to be controlled by $[g_c P / g(\Delta\rho) V u_t]\ [(1-\epsilon)/\epsilon]^{-1/2}$. It appears that the suspension problem should be similar in both mixing vessels and pipelines. Therefore, as an extension of the previous work, the model developed for particle suspension by mechanical mixers has been applied to the minimum transport conditions in horizontal conduits.

Attention will be confined to nonflocculated slurries outside of their compaction zone. The analysis of flocculated slurries is complicated by the fact that measurements of solid particle size and density are not necessarily indicative of those of the flocs. In addition suspensions in compaction tend to behave as homogeneous non-Newtonian fluids (*12*).

PROPOSED CORRELATION

In the transport of a settling, or heterogeneous, slurry in a horizontal conduit the vertical lift forces overcoming the settling tendency are provided by the turbulent velocity fluctuations. At the minimum transport conditions these must just be at equilibrium. From theoretical considerations Weisman and Efferding showed, for dilute suspensions with particles obeying Stokes's law, that when the settling and suspending forces on a single particle are in equilibrium

$$P_p = \frac{g V_p (\Delta\rho) u_o}{4 g_c} \qquad (1)$$

As the concentration of the suspension is increased, the particle settling velocity is reduced by the presence of other particles. It has been shown (*7*) that for nonflocculated suspensions, where D/D_p is large, the ratio of the actual particle settling rate to the settling rate in an infinitely dilute medium is a unique function of the void fraction. Hence for suspensions of normal concentrations

$$P_p = \left(\frac{g V_p (\Delta\rho) u_o}{4 g_c} \right) \cdot \phi(\epsilon) \qquad (2)$$

It is desirable to express the value of P_p for the particles at the point of suspension in terms of the mean value for all the particles. The particles just at the point of suspension will have a

Closely Sized Particles					
Symbol	Ref.	Material	$1-\epsilon$	D	D_p
- - - - - -	5	Sand	.05	150 mm	50-500 μ
—·—	5	Sand	.05	37.5 mm	50-500 μ
— — —	5	Sand	.15	150 mm	50-2000 μ
·—··	5	Sand	.15	600 mm	50-2000 μ
○	10	Sand	.002-.26	2-3 in	193 μ
●	8	Steel	.006-.03	1/2 in	.0149 in.
⦶	8	Steel	.019-.05	1/2 in	.072 in.
+	8	Glass	.03-.13	1/2 in	.0114 in.
■	8	Glass	.02-.13	1/2 in	.0314 in.
▲	8	Lead	.017-.037	1/2 in	.0505 in.

Mixed Particle Sizes					
Symbol	Ref.	Material	$1-\epsilon$	D	$(D_p)_{85}$
□	10	Mixed Sand	.03 - .25	3 in	1250 μ
⊗	10	Mixed Sand	.03 - .33	2 in	1250 μ
⊙	10	Coarse Sand	.02 - .135	3 in	1900 μ
○	10	Coarse Sand	.03 - .13	2 in	1900 μ
◭	4	$B_a SO_4$	.025 av.	1 in	35 μ
◐	4	Tungsten	.0035 av.	1 in	12.5 μ

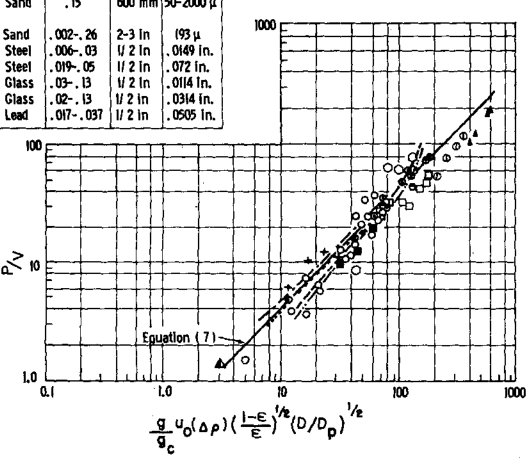

Fig. 1. General correlation of minimum power requirements for slurry transport.

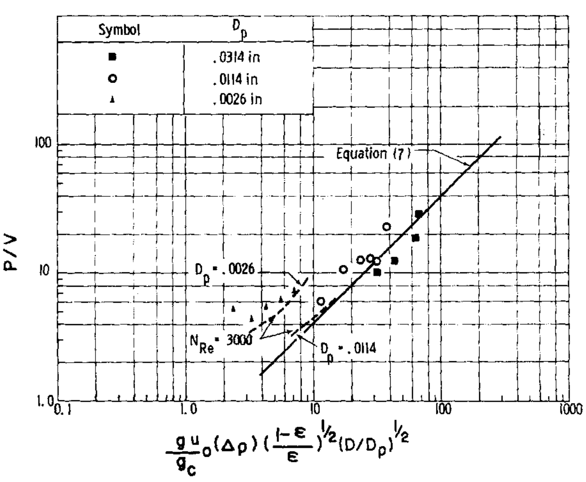

Fig. 2. Minimum transport power requirements for small glass particles in ½-in. diameter pipe.

lower power input than the average since they are closest to the wall and see less of the turbulent fluctuations. If it is assumed that the power input at a distance of the order of one particle diameter from the wall is controlling, then the ratio $P_p/(P_p)_{avg}$ can be expressed as a function of D/D_p. Hence

$$(P_p)_{avg} = \left(\frac{gV_p(\Delta\rho)u_o}{4g_c}\right) \cdot \phi(\epsilon) \cdot \phi\left(\frac{D}{D_p}\right) \qquad (3)$$

The ratio of $(P_p)_{avg}/V_p$ can be replaced by the ratio of the power dissipated by all the particles through vertical motion to the volume of all particles, $(P_p)_{total}/V(1-\epsilon)$. Combining terms one has

$$(P_p)_{total} = \left(\frac{gV(\Delta\rho)u_o}{4g_c}\right) \cdot \phi(\epsilon, 1-\epsilon) \cdot \phi\left(\frac{D}{D_p}\right) \qquad (4)$$

It is to be expected that the ratio of the power dissipated by the particle through vertical movements to the power dissipated in the system will depend on $(1-\epsilon)$, D/D_p, and the Reynolds number. It shall be assumed that, at the minimum transport conditions, the Reynolds number effect is small. Then

$$\left(\frac{g_cP}{gV(\Delta\rho)u_o}\right) = \phi^1(\epsilon, 1-\epsilon) \cdot \phi^1\left(\frac{D}{D_p}\right) \qquad (5)$$

The validity of the assumption that the Reynolds number effect is small will be evaluated by application of the expression to the available data.

CORRELATION OF AVAILABLE DATA

Based on the correlation of data for particle suspension by mechanical mixers, it appears reasonable to postulate that for a given solid particle and conduit P/V should be proportional to $[(1-\epsilon)/\epsilon]^{1/2}$. Examination of the experimental data, particularly those of Smith (*10*), showed this proportionality to be valid. Further examination of the experimental data indicates the minimum transport power to vary with $(D/D_p)^{1/2}$. Hence one obtains

$$P/V \,\alpha \left(\frac{gu_o(\Delta\rho)}{g_c}\right) \left(\frac{1-\epsilon}{\epsilon}\right)^{1/2} \left(\frac{D}{D_p}\right)^{1/2} \qquad (6)$$

Figure 1 shows the available experimental data (*4, 5, 8, 10*) plotted in this fashion. The data are correlated by

INFORMATION RETRIEVAL*

Key Words: Thermodynamics-8, Physical Properties-8, Properties (Characteristics)-8, Volumetric-8, Mixtures-8, Equilibrium-9, Phase Equilibrium-9, Fluids-9, Cryogenics-9, Equation of State-9, Predicting-9, Correlating-9, Helium-1, Neon-1, Argon-1, Krypton-1, Xenon-1, Methane-1, Ethane-1, Ethylene-1, Acetylene-1, Propane-1, Propylene-1, Hydrocarbons-1, Oxygen-1, Carbon Monoxide-1, Carbon Dioxide-1, Nitrogen-1, Hydrogen-1, Potential Functions-10, Kihara-, Parameters-10, Virial Coefficients-10.

Abstract: The volumetric properties of sixteen fluids of interest in cryogenic engineering have been used to compute second virial coefficients which, in turn, were fitted to theoretical expressions based on the Kihara potential. The Kihara parameters obtained enable good predictions to be made of low temperature volumetric properties and phase equilibria.

Reference: Prausnitz, J. M., and A. L. Myers, **A.I.Ch.E. Journal, 9,** No. 1, p. 5 (January, 1963).

Key Words: Stirred Vessels-1, Turbine Impellers-4, Water-5, Sodium Chloride-5, Inlet Flow Rates-6, Revolutions per Minute-6, Mean Concentrations-7, Concentration Fluctuations-7, Mixing-8, Mechanism of Fluid Mixing-9, Turbulent Decay-9, Conductivity Probe-10, Electronic Equipment-10.

Abstract: The following statistical concentration parameters of a stirred, baffled vessel are measured with a conductivity probe and electronic equipment: temporal mean, total root-mean-square fluctuation, and spectral distribution of fluctuations. Three markedly different zones exist, the generation region within the impeller, the decay region which starts in the horizontal fluid sheet issuing from the impeller, and the recirculating flow region in the vessel. Generation of concentration fluctuations by the impeller is described by a model involving gross mixing, without significant decay in the wake of each flat blade. Mean concentrations are remarkably constant throughout the vessel.

Reference: Manning, F. S., and R. H. Wilhelm, **A.I.Ch.E. Journal, 9,** No. 1, p. 12 (January, 1963).

Key Words: A. Binary Gas-5, Catalyst-5, Pressure-6, Flux Ratio-7, Steady Counterdiffusion-8, Effective Diffusion Coefficient-8, Knudsen Diffusion-8, Bulk Diffusion-8, Intermediate Range-8, Tortuosity-9, Surface Transport-9, Porous-, Bidisperse-, Theoretical-, Experimental-.

Abstract: In steady counterdiffusion of two gases in porous medium (the Wicke-Kallenbach experiment) the flux ratio is independent of total pressure and different from unity over the entire range from Knudsen to bulk diffusion. The intermediate range is examined theoretically and experimentally, and a new method is given for calculating the effective diffusion coefficient from counterdiffusion data.

Reference: Rothfeld, Leonard B., **A.I.Ch.E. Journal, 9,** No. 1, p. 19 (January, 1963).

Key Words: Phase Behavior-8, Critical Point-8, Multicomponent Hydrocarbon Mixtures-8, All Types of Hydrocarbons-8, Pseudocritical Pressure-1, Pseudocritical Density-1, Normal Boiling Point-1, Vapor Pressure Data-1, Composition of Mixture-1, Critical Pressure-2, Critical Density-2.

Abstract: Methods have been developed for the prediction of the critical pressures of multicomponent hydrocarbon mixtures and the critical densities of binary hydrocarbon mixtures of known composition. These mixtures may contain normal and isoparaffins, olefins, acetylenes, naphthenes, and aromatics. The correlations are based upon the mole fraction of the low-boiling component in the mixture and relate dimensionless critical pressure and critical density ratios to a boiling parameter. The expected error for critical pressure is 1.4% and for critical density is 1.5%.

Reference: Grieves, Robert B., and George Thodos, **A.I.Ch.E. Journal, 9,** No. 1, p. 25 (January, 1963).

(Continued on page 137)

* For details on the use of these key words and the A.I.Ch.E. Information Retrieval Program, see **Chem. Eng. Progr., 57,** No. 5, p. 55 (May, 1961), No. 6, p. 73 (June, 1961); **58,** No. 7, p. 9 (July, 1962).

$$\left(\frac{g_c P}{gV(\Delta\rho)u_o}\right) = 0.4\left(\frac{1-\epsilon}{\epsilon}\right)^{1/2}\left(\frac{D}{D_p}\right)^{1/2} \quad (7)$$

The agreement between Equation (7) and the data is good, particularly in view of the wide variation in the conditions covered and the scatter of the original data. It may be seen that materials as different as sand, glass, steel, and lead are included. Particle sizes vary from 12.5 to 2,000 μ and pipe sizes from ½ to 24 in. The data of Durand and Condolios (*5*) are presented in terms of curves computed from their correlation, since very few of their actual data points are available.

In order to bring Smith's data (*10*) for mixed sands into line with those for uniform particles it was necessary to use a particle diameter representative of the large size particles in the mixture. Such behavior is to be expected in coarsely graded material; the fines should be most easily suspended. This was observed by Blatch (*3*), who pointed out that for closely sized particles, large quantities of solids suddenly begin to be carried in suspension at a given velocity. For coarsely graded solids the change is more gradual, with the fines being the first to be suspended. It is seen from Figure 1 that an adequate correlation of the available data on mixed sizes is achieved by use of $(D_p)_{85}$ for the appropriate particle diameter.

Also shown on Figure 1 are the data points of Cairns (*4*) for tungsten and barium sulfate slurries. With the particle diameters taken as $(D_p)_{85}$ these data agree well with the predicted values. This agreement is particularly interesting in view of the small size and high density of Cairn's particles.

Since in the derivation of the correlation it was assumed that the particles obey Stokes' law, it might be expected that deviations would be obtained with the larger size particles. This however is not the case. The correlation appears to hold throughout the intermediate law range and into the Newton's law range.

At power levels below those predicted by Equation (7) a portion of the slurry will remain stationary on the bottom of the conduit. A difficulty develops however if this prediction is extrapolated to very slowly settling particles in small pipelines. Here Equation (7) may predict P/V values lower than those which exist at the onset of turbulence. Since turbulent velocity fluctuations are needed to provide the vertical lift forces, it is to be expected that the actual power requirements would be in excess of those predicted.

Figure 2 shows the data of Murphy et al. (*8*) for glass particles. As may be seen, the two largest sizes are in agreement with Equation (7), but those for the smallest size are not. If the assumptions made are correct, the higher power requirement for the small size particles should correspond to the power dissipated at the onset of full turbulence. It shall be assumed that turbulence is fully developed at a Reynolds number of 3,000. This is in general accord with the observations of Thomas (*12*) on flocculated slurries in compaction where particle settling rates are very low. There the minimum transport condition occurs at modified Reynolds numbers between 3,000 and 4,800 with the average value of N_{Re} at 3,500. The data for the smallest size glass particles appear to be in good agreement with the dashed curve showing the P/V values which occur at a Reynolds number of 3,000. In computing the Reynolds number, the average properties of the suspension were used. The viscosity was taken from the correlation of Happel (*6, 7*) which predicts suspension viscosity as a function of the void fraction and liquid viscosity. The power dissipation was computed from the actual pressure drop data reported by Murphy et al.

On the basis of these data the minimum power requirements for transport of nonflocculated slurries appear to be those at a Reynolds number of about 3,000 whenever such power exceeds that computed by Equation (7). It is thus desirable to be able to compute the total power dissipated at this critical Reynolds number. Newitt (*9*) has correlated his data on the pressure drop of slurries of graded particle sizes transported as a heterogeneous suspension by

$$\frac{h_m - h_w}{(1-\epsilon)h_w} = 1{,}100\left(\frac{gD\rho^3_m}{G^3}\right)u_o\left(\frac{\rho_s}{\rho_l}-1\right) \quad (8)$$

If h_w is replaced by the appropriate terms of the Fanning equation and use is made of the fact that

$$\frac{g_c P}{gV} = hG \quad (9)$$

Equation (8) can be rearranged to yield

$$\left(\frac{g_c(P-P_l)}{gVu_o(\Delta\rho)}\right) = 2{,}200 f(1-\epsilon)\left(\frac{\rho_m}{\rho_l}\right) \quad (10)$$

The total power requirements are given by

$$\left(\frac{g_c P}{gVu_o(\Delta\rho)}\right) = 2{,}200f(1-\epsilon)\,\frac{\rho_m}{\rho_l} + \frac{2fG^3}{Dgu_o(\Delta\rho)\rho^2_m} \quad (11)$$

For $N_{Re} = 3{,}000$ this may be simplified to

$$\left(\frac{g_c P}{gVu_o(\Delta\rho)}\right) = 26.4\,(1-\epsilon)\,\frac{\rho_m}{\rho_l} + \frac{6.46\cdot 10^8\,\mu^3_m}{D^4\rho^2_m u_o(\Delta\rho)g} \quad (12)$$

By equating (7) and (12) a critical settling rate is obtained:

$$(u_o)_{\text{critical}} = \frac{6.46\cdot 10^8 \mu^3_m}{[0.41(1-\epsilon/\epsilon)^{1/2}(D/D_p)^{1/2} - 26.4(1-\epsilon)\,(\rho_m/\rho_l)][D^4\rho^2_m(\Delta\rho)g]} \quad (13)$$

Minimum transport conditions for particles having settling rates above this value are determined by Equation (7). Minimum transport conditions for particles with lower settling rates occur at the onset of full turbulence. It is apparent that particle size is not the only parameter which establishes whether a particle will have a settling rate above or below the critical value.

In the use of Equations (12) and (13) it is suggested that μ_m be obtained with a correlation such as that of Happel (*6, 7*) which predicts suspension viscosity as a function of liquid viscosity and solids fraction. Caution should be used in applying both equations, since they are based on limited data.

DISCUSSION

The successful correlation of the available experimental data would appear to justify the original supposition that the mechanism for particle suspension in conduits is similar to that in mechanical mixers. It may be concluded that in order to transport a nonflocculated slurry outside its compaction zone without deposition of solids, it is necessary that the flow be turbulent. For very slowly settling particles in small lines, it appears that the only requirement is that the flow be fully turbulent. For more rapidly settling particles or larger conduits, greater eddying movements are necessary to supply the vertical forces which keep the particle in suspension. These are governed by the dimensionless grouping $[g_cP/gV(\Delta\rho)u_o]\;[(1-\epsilon)/\epsilon]^{-1/2}(D/D_p)^{-1/2}$ as shown in Equation (7).

It must be noted that all the data to which the correlation has been applied pertain to aqueous slurries. The only data on a nonaqueous slurry known to the author (*1, 2*) apply to a highly flocculated system. Therefore it is not fully certain that the effect of the properties of the suspending fluid is fully accounted for by the present correlation. In addition the derivation of the correlation assumed that the effect of Reynolds number was not important. It seems quite probable that there is a small Reynolds number effect which is masked by the scatter of the available data.

Care should be used in applying Equation (7) to very dilute suspensions. For an infinitely dilute suspension, Equation (7) would predict zero power requirements. As shown by Thomas (*12, 13*) this is obviously not the case; hence the present correlation should not be applied to concentrations below those for which it has been shown applicable [$(1-\epsilon)$ not less than 0.2%]. The present correlation covers the usual operating concentration range.

The dimensionless group $[g_c P / g V (\Delta\rho) u_o]$ would seem to have fundamental significance in fluid-solid systems. In addition to its use in the correlation of minimum transport conditions, the group appears in the correlation of the incremental pressure drop due to slurry flow in pipelines, and in a similar form in the correlation of power requirements for slurry suspension in mixing vessels.

NOTATION

D = pipe diameter, ft.
D_p = average particle diameter, ft.
$(D_p)_{85}$ = diameter such that 85 wt. % of the particles are smaller than $(D_p)_{85}$, ft.
f = friction factor, dimensionless.
g = local gravitational acceleration, ft./sec.^{2}
g_c = mass acceleration/force conversion factor (lb. mass) (ft.)/(lb.-force) sec.^{2}
G = mass velocity, lb./sq.ft. sec.
h_m = head loss of slurry, ft./ft.
h_w = head loss of water flowing at same velocity as slurry, ft./ft.
P = total power input, ft.-lb.-force/sec.
P_l = power input based on head loss of suspending fluid alone & total mass velocity = $h_w G$, ft.-lb.-force/sec.
P_p = vertical component of power input to single particle when suspending and settling forces are in equilibrium, ft.-lb.-force/sec.
$(P_p)_{avg}$ = average vertical component

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INFORMATION RETRIEVAL

Key Words: Single Phase-1, Mixed Phase-1, Liquid-1, Tracer-1, Pulse Function-1, Residence Time-2, Liquid Distribution-2, Porous Packing-4, Nonporous Packing-4, Voids-4, Packed Bed-5, Diameter-6, Flow Rate-6, Diffusivity-6, Variability-7, Holdup-7, Breakthrough-7, Contacting Efficiency-8.

Abstract: Liquid residence time distributions were obtained for downflow operations in packed beds with pulse function injection of radioactive tracers used. Both single and mixed phase flow were studied with porous and nonporous cylindrical packings. The spread in residence time distributions, that is variability, was found to be composed of three additive channels, from diffusion of material in and out of stagnant pockets of liquid, and from pore diffusion. The measured variability correlated well with particle Reynolds number for each system.

Reference: Glaser, M. B., and Ira Lichtenstein, **A.I.Ch.E. Journal, 9,** No. 1, p. 30 (January, 1963).

Key Words: Diameter-6, Temperature-6, Emissivity-6, Porosity-6, Size-6, Shape-6, Void Fraction-6, Conductivity-7, Cross Section-7, Attenuation-7, Conduction-8, Heat Transfer-8, Mechanisms-8, Radiation-8, Transport-8, Theory-8, Absorption-9, Packed Beds-9, Scattering-9, Transmission-9, Aluminum Oxide-10, Black Body-10, Cylinders-10, Glass-10, Grains-10, Particle-10, Silicon Carbide-10, Spheres-10, Steel-10, Transmission-10, Incident-, Source-, Spectral-, Thermal-.

Abstract: Radiant heat transfer in packed beds of aluminum oxide, silicon carbide, steel, and glass spheres, cylinders, and grains was studied experimentally. Effective scattering and absorption cross sections were determined from measurements of radiant transmission, and radiant conductivities were calculated from these cross sections. Backscattering was found to be the principle mechanism of attenuation for all of the packings. Absorption was a significant mechanism only for the silicon carbide grains. The effect of source temperature and the relationship between the cross sections and the emissivity and transmissivity of the materials was studied.

Reference: Chen, John C., and Stuart W. Churchill, **A.I.Ch.E. Journal, 9,** No. 1, p. 35 (January, 1963).

Key Words: Ion Exchange-9, Equilibria-9, Cation- , Aqueous-5, Concentration-6, Dilute-5, Hydrogen-2, Sodium-1, Copper-2, Dowex 50-1, Binary- , Ternary- , Selectivity-7.

Abstract: Cation exchange equilibria between Dowex 50W-X8 resin and aqueous solution of cupric nitrate, nitric acid, and sodium nitrate have been studied in binary and ternary mixtures. For solutions with total cation concentrations of 0.1, 0.05 and 0.01N it was found that the equilibria for any two ions were essentially the same in binary and ternary mixtures. Single valued selectivity coefficients were determined which characterize these data quite well over the concentration range studied.

Reference: Pieroni, Leonard J., and Joshua S. Dranoff, **A.I.Ch.E. Journal, 9,** No. 1, p. 42 (January, 1963).

Key Words: Flow-8, Fluid Flow-8, Hydrodynamics-8, Stability-8, Transition-8, Stability Parameter-9, Turbulence-9, Pipe Flow-9, Annular Flow-9, Parallel Plate Flow-9, Fluids-9, Non-Newtonian- , Power Law- , Reynolds Number-6, Velocity-6, Flow Rates-6, Properties (Characteristics)-6, Transition-7, Stability-7.

Abstract: A generalized stability parameter is proposed which is independent of geometry and for rectilinear Newtonian flow is proportional to the critical Reynolds number $(d_e \bar{v} \rho/\mu)$, where d_e is an equivalent diameter defined by the requirement that $f = 16\ N_{Re}^{-1}$ for laminar flow in the three geometries considered.
The theoretical variation of the critical Reynolds number with radius ratio r_1/r_2 for annular flow exhibits a maximum value equal to 2,462 for $r_1/r_2 = 0.15$. This maximum is verified quantitatively by available literature data.
The parameter is also shown to be valid for isothermal and heated pipe flow of power-law non-Newtonian fluids.

Reference: Hanks, Richard W., **A.I.Ch.E. Journal, 9,** No. 1, p. 45 (January, 1963).

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INFORMATION RETRIEVAL

Key Words: Heat Transfer-8, Momentum Transfer-8, Analogy-8, Laminar Flow-8, Physical Properties-8, Thermal Conductivity-8, Viscosity-8, Prandtl Number-8, Transport-8, Rates-8, Plasma-9, Correlations-9, Plasma Generator-10, Helium-1, Entrance-6, Energy Loss-6, Sonic Velocity-6, Reynolds Number-6, Energy-6, Heat Transfer Coefficient-7, Friction Factor-7, High Temperature-7.

Abstract: The exit gas of a plasma generator was cooled in a three-unit, water-cooled heat exchange system, which provided heat transfer and pressure loss data at length to diameter ratios of 11, 19, and 27. The heat transfer data correlated with the Graetz number, and the momentum transfer results correlated with $f = 16/N_{Re}$. Analogies were considered and an improved temperature correction suggested. In addition several approximate equations for certain limiting conditions have been obtained.

Reference: Wethern, R. J., and Robert S. Brodkey, **A.I.Ch.E. Journal, 9,** No. 1, p. 49 (January, 1963).

Key Words: Heat Transfer-7, Heating-10, Cooling-10, Boiling-8, Vaporization-8, Burnout-8, Organic Fluid-9, Ethylene Glycol-9, Properties-6, Turbulence-6, Friction-8, Axial Flow-13, Swirl Flow-13.

Abstract: Measurements were made of heat transfer rates and critical heat flux for atmospheric pressure pool boiling, and of adiabatic and diabatic friction factors, nonboiling and subcooled boiling heat transfer rates, and burnout heat fluxes for both axial and twisted tape swirl flow forced convection of pure ethylene glycol through electrically heated tubular test sections. At the higher Reynolds numbers and heat fluxes axial flow nonboiling heat transfer coefficients show a dependence of Nusselt number on $N_{Re}^{0.98}$ rather than the traditional $N_{Re}^{0.80}$. Swirl flow nonboiling heat transfer coefficients for both ethylene glycol and water are correlated by a single equation.

Reference: Gambill, W. R., and R. D. Bundy, **A.I.Ch.E. Journal, 9,** No. 1, p. 55 (January, 1963).

Key Words: Mass Transfer-8, Heat Transfer-8, Momentum Transfer-8, Packed Beds-4, Distended Beds-4, Spheres-4.

Abstract: Simultaneous mass, heat, and momentum transfer were investigated for the flow of air through packed and distended beds of spheres saturated with water. Similar relationships for both types of beds were obtained when the resulting transfer factors j_d and j_h were related to the modifed Reynolds number $N_{Re'} = D_p\, G/\mu(1-\epsilon)$. The Ergun relationship for packed beds has been found to apply to both types of beds investigated.

Reference: McConnachie, J. T. L., and George Thodos, **A.I.Ch.E. Journal, 9,** No. 1, p. 60 (January, 1963).

Key Words: Enthalpy-8, Hydrogen Bonding-8, n-Butanol-1, Benzene-1, Solutions (Binary)-2, Temperature-6, Pressure-6, Composition-6, Enthalpy-7, Charts-7, Calorimeter-10, Adiabatic-, Flow-.

Abstract: Enthalpies of n-butanol and binary mixtures of 75, 50, and 25 mole % n-butanol in benzene were measured in an adiabatic flow calorimeter at temperatures from 250° to 550°F. and pressures from 20 to 1,000 lb./sq. in. abs. Pressure-enthalpy charts with an estimated accuracy of ± 1% and related diagrams are presented for these highly nonideal systems.

Reference: Shannon, Paul T., David B. Gustafson, and Patrick S. O'Neill, **A.I.Ch.E. Journal, 9,** No. 1, p. 64 (January, 1963).

Key Words: Viscosity-9, Ammonia-9, Gases-9, Correlations-9, Unsteady State-8, Flow-8, Fluid Flow-8, Viscosity-8, Density-8, Critical-8, Properties (Characteristics)-8, Physical Properties-8, Ammonia-1, Nitrogen-1, Pressure-6, Temperature-6, Viscosity-7, Transpiration-10, Computers-10, IBM-650-10.

Abstract: The unsteady state flow of ammonia gas has been investigated to determine the viscosity of this substance at elevated pressures (250 to 5,000 lb./sq. in.) and moderate temperatures (100° to 200°C). A transpiration unit, calibrated with nitrogen, was used. The differential equation for the unsteady state flow was solved with the aid of an IBM-650 digital computer. A correlation between residual viscosity and density has been developed and used to determine the critical viscosity of ammonia, 2,395 × 10^{-6} centipoises.

Reference: Shimotake, Hiroshi, and George Thodos, **A.I.Ch.E. Journal, 9,** No. 1, p. 68 (January, 1963).

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of power input to single particle, ft.-lb.-force/sec.

$(P_p)_{total}$ = vertical component of power input to all particles, ft.-lb.-force/sec.

N_{Re} = Reynolds number, dimensionless

u_o = free settling velocity of particle in infinitely dilute suspension, ft./sec.

u_t = relative velocity between particle and fluid in turbulent region = $1.74\left[\dfrac{gD_p(\Delta\rho)}{\rho_l}\right]^{1/2}$ ft./sec.

V = system volume, cu.[1] ft.

V_p = volume of individual particle, cu. ft.

Greek Letters

ϵ = liquid fraction, dimensionless

μ = size, μ (on figures)

μ_1 = viscosity of suspending liquid, lb.-mass/sec.-ft.

μ_m = viscosity of mixture, lb-mass/sec.-ft.

ρ_l = density of suspending liquid, lb.-mass/cu. ft.

ρ_m = density of slurry mixture, lb.-mass/cu.ft.

= difference in density between solid and liquid, lb.-mass/cu.ft.

τ_w = wall shear stress, lb.-force/sq.ft.

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