Power requirements for pulp suspension fluidization

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ABSTRACT: *The power required to create a turbulent or fluidized state within a semi-bleached kraft (SBK) softwood pulp was determined in a concentric-cylinder high-shear device. The apparent viscosities of the fluidized suspensions were estimated using turbulence theory and appropriate mixer characterization techniques. For example, estimates of the apparent viscosity of a fluidized 10% consistency SBK suspension ranged from 0.9 to 3.9 Pa·s—one to four thousand times that of water. Using these estimated viscosities, the discrepancies between past estimates of the power needed to create a fluidized state and experimental values were reconciled.*

KEYWORDS: *Dispersions, dissipation factor, fluidization, kraft pulps, medium consistency, mixing, power factor, softwood pulps, specifications, turbulence, viscosity.*

Many unit operations in pulp and paper manufacture are critically dependent on the flow characteristics of fiber suspensions. These characteristics span a range of behavior, from "plug flow" where there is no relative motion among the fibers, through a "mixed flow" regime where one part of the suspension has plug behavior while adjacent zones are in motion, to "fully turbulent flow" in which there is a high degree of relative motion throughout the suspension. These regimes are displayed by pulp suspensions in pipe flow *(1)*, mixing devices *(2)*, and pumps *(3)*.

The turbulent regime is of particular interest here because the suspension exhibits properties commonly associated with Newtonian fluids. For example, in pipe flow, the friction loss approaches that of water. Because of this, pulp suspensions in a turbulent state are often referred to as "fluidized." The use of this term has been questioned in recent work *(4)*; therefore, it is useful to discuss its meaning and implications in pulp suspensions.

In chemical engineering, fluidization generally refers to a unit operation in which a bed of solid particles is mobilized by passage of a liquid or gas through the particles *(5)*. The resulting suspension adopts characteristics of a fluid. For pulp suspensions, we adopt a more generic definition, but one that still reflects a particulate system that behaves like a fluid due to relative motion among solid particles—in this case, the pulp fibers. In this state, the pulp suspension has key characteristics of a fluid, namely that it flows when sheared and transmits pressure in all directions. These attributes yield another characteristic common to fluids but not solids, a pressure energy. Thus, the energy balance is described by the Bernoulli equation. As a result, pressure energy can be recovered from kinetic energy. An important practical consequence of this is that suspensions can be pumped by centrifugal pumps. In contrast, in the non-fluidized "plug flow" regime, pulp suspensions can be pumped only by positive displacement pumps.

An implicit assumption in fluidization is that the suspension behaves as a continuum. This requires that the size of the discrete elements in the system be smaller than the dimensions of the flow. This condition does not occur in all unit operations in pulp and paper manufacture, for example, in screens and refiners, but it does occur in many others where

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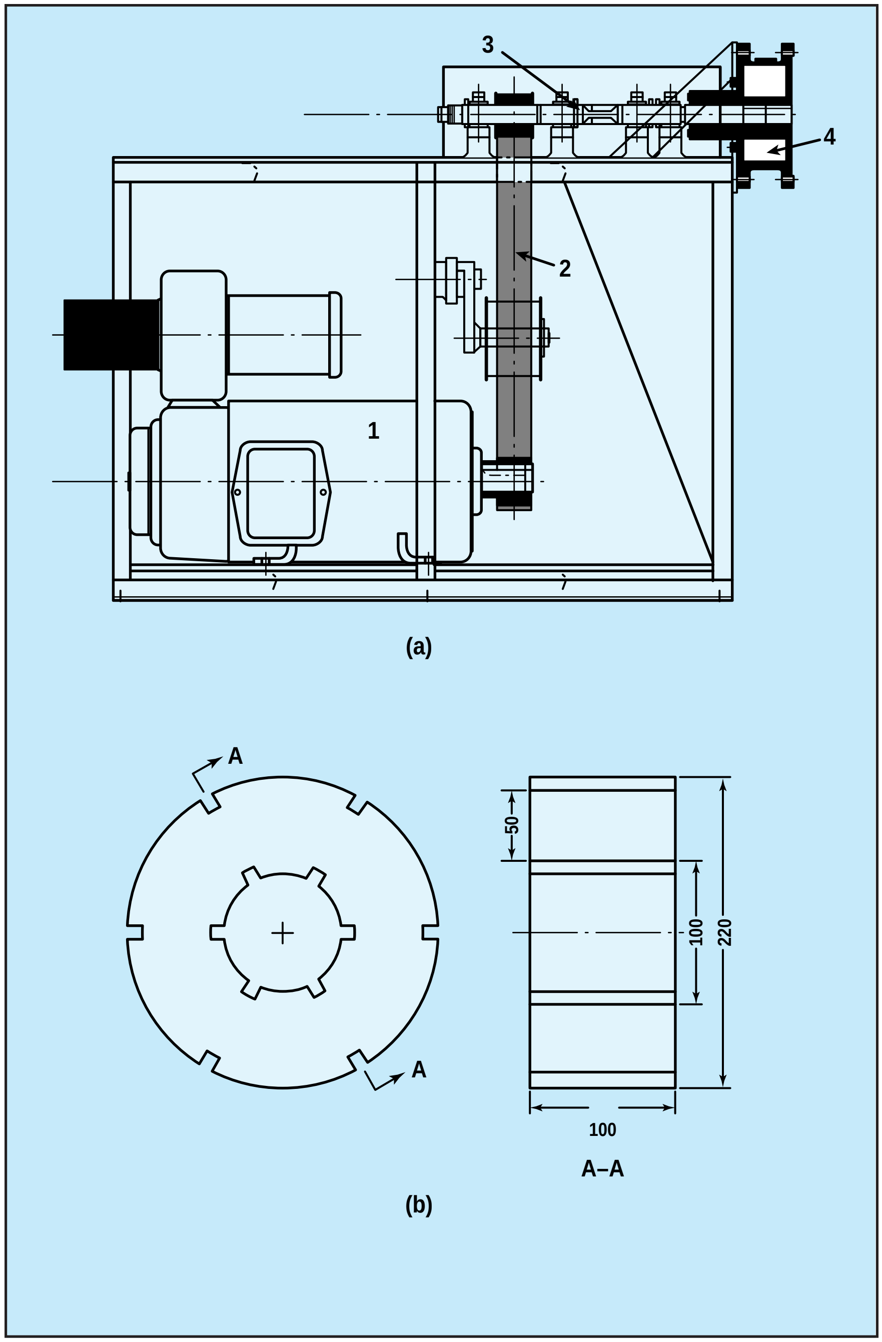
1. Rotary shear device. (a) side view showing the (1) 22.4 kW dc motor, (2) toothed drive belt, (3) instrumented shaft, and (4) test chamber; and (b) detail of test chamber *A* (dimensions in millimeters).



flow dimensions are larger than approximately 5 mm. When it does, an important further consequence of fluidization is that the suspension has an apparent viscosity. In common with other particulate suspensions, the viscosity of the suspension is greater than the viscosity of the suspending medium.

In summary, turbulent fiber suspensions may exhibit properties of a turbulent fluid, and when this occurs may be called fluidized. However, because this occurs only under restricted conditions, it is useful to have quantitative criteria for determining when fluidization takes place. Past attempts at characterizing suspensions for this purpose are reviewed below.

Fluidization implies relative motion among fibers which leads to energy dissipation. Thus one potential method of quantifying fluidization is through power and energy expenditure. This concept was introduced by Wahren *(6)* in his estimation of power dissipation per unit volume for the onset of fluidization, ε_F using the yield stress of the fiber network, τ_y (the stress required to initiate flow under shear), and the expression for power dissipation in laminar flow, $\varepsilon = \tau^2/\mu$. This gave:

$$\varepsilon_F = \tau_y^2/\mu \qquad (1)$$

Substituting published expressions of the form $\tau_y = aC_m^{\ b}$ for the suspension yield stress and using the viscosity of water, Wahren obtained the following expression for ε_F:

$$\varepsilon_F = 1.2 \times 10^4 C_m^{\ 5.3} \qquad (2)$$

where C_m is the suspension mass concentration given as a percent and ε_F is in W/m^3.

In later work, Gullichsen and Harkonen *(7)* visually determined the onset of fluidization in a rotary device. They defined fluidization as the onset of turbulent motion throughout a vessel. This point was also characterized by a sharp increase in the torque on the rotor. Using their data, an expression for ε_F was obtained *(8)*:

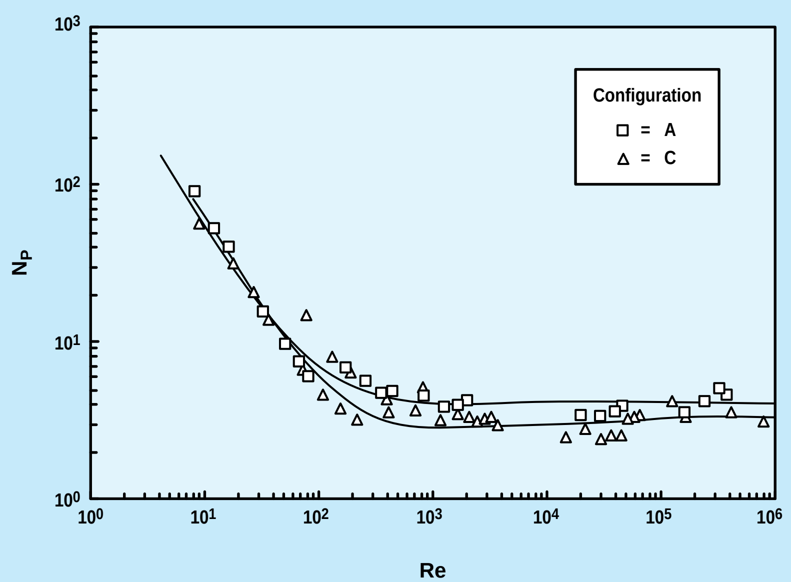
$$\varepsilon_F = 3.4 \times 10^2 C_m^{\ 3.4} \qquad (3)$$

It can be noted that, for any given suspension concentration, the dependence of power dissipation for fluidization on consistency measured by Gullichsen and Harkonen is approximately two orders of magnitude less than that estimated by Wahren. This may be due to differing definitions of fluidization *(2)*. However, a more likely explanation lies in Wahren's use of the viscosity of water in Eq. 1. If a pulp suspension behaves as a fluid, the suspension has an apparent viscosity which is most certainly larger than that of water. Therefore

I. Rotor/housing dimensions used in tests

Chamber component	*Test configuration* *A*	*B*	*C*	*D*
Housing				
Diameter, D_T, mm		220		130
Depth, mm	←	100	→	100
Number of vanes		6		6
Baffle dimensions, mm		10x10		10x10
Rotor				
Diameter, *D*, mm	100	100	70	100
Depth, mm	100	100	100	100
Number of vanes	6	6	6	6
Lug dimensions, mm	10x10	25x10	10x10	10x10
Gap width, mm	50	50	65	5
Volume of chamber, L	3.16	3.41	3.47	0.73
D_T/D	2.2	2.2	3.14	1.3

2. Rotor power number versus Reynolds number for the rotor/housing configurations *A* and *C*. Fluids used: water, water/glycerol solutions, Shell Omala 1000, Dow Corning 200.



the use of the viscosity of water to estimate the power required to fluidize a pulp suspension is inappropriate.

In more recent work, Bennington *et al. (2)* characterized in greater detail the flow regimes that exist in the type of rotary device used by Gullichsen and Harkonen. It was found that as rotational speed increased, there was a growing cavity of pulp having a largely tangential motion bounded by stationary pulp. In this mixed regime, the pulp in motion behaved in a fluid-like manner, but was not in turbulent flow; the outer stationary plug of pulp is analogous to the plug in the "plug flow" regime in pipe flow. As the rotor speed increased, the size of the active cavity increased until it reached the vanes on the outer housing. As these vanes interacted with the flow, the flow became turbulent and adopted a strong radial motion leading to a fully turbulent regime throughout the vessel. This was the well defined visual event used by Gullichsen and Harkonen to signify the onset of fluidization. Achieving this in a pump was the basis of development of a centrifugal pump for medium consistency pulps *(3)*.

Although the definition of fluidization remains somewhat arbitrary, it is clear that pulp suspensions can be made to behave as fluids in process equipment. Fluidization in this context is therefore an important and useful concept for engineering purposes. The objective of this study is to increase our knowledge of two aspects of pulp fluidization: the power requirements for fluidization and the apparent viscosity of the fluidized suspensions.

Experimental procedures and results

We carried out tests in a rotary shear device having a concentric-cylinder geometry. The pulp suspension was contained in a chamber bounded by an inner rotor and an outer housing. The rotor was powered by a 22.4 kW variable-speed dc drive that permitted shaft speeds of 524 rad/s (83 s^{-1}). The rotors and housing had vanes that protruded into the suspension to minimize slip at the interface between the suspension and chamber. The front face of the shear tester was a clear Lexan® plate that permitted viewing and videotaping of flow profiles. The shear tester is illustrated in **Fig. 1**. The dimensions of the rotor/housing combinations used in this study are given in **Table I**.

Semibleached kraft (SBK) pulp fiber suspensions of the desired mass concentrations were prepared from never-dried pulp obtained from two western Canadian mills. A measured volume or weight of suspension was added to the test chamber and a test conducted. A standard test consisted of accelerating the rotor at 52.4 rad/s^2 to 524 rad/s, holding this maximum speed for 5 s, followed by deceleration at 52.4 rad/s^2 to rest. The torque and rotational speed were measured throughout the test at 0.04 s intervals. Torque measurements were made to an accuracy of $\pm$ 0.3 N·m with strain gauges built into the shaft of the shear tester. The bearing friction was measured by operating the shear tester with the chamber empty. This friction torque was subtracted from all measured torques. The shaft rotational speed was determined using a remote optical sensor accurate to 1 rpm over the range of 50 to 5000 rpm.

Determination of power dissipation, ε_F

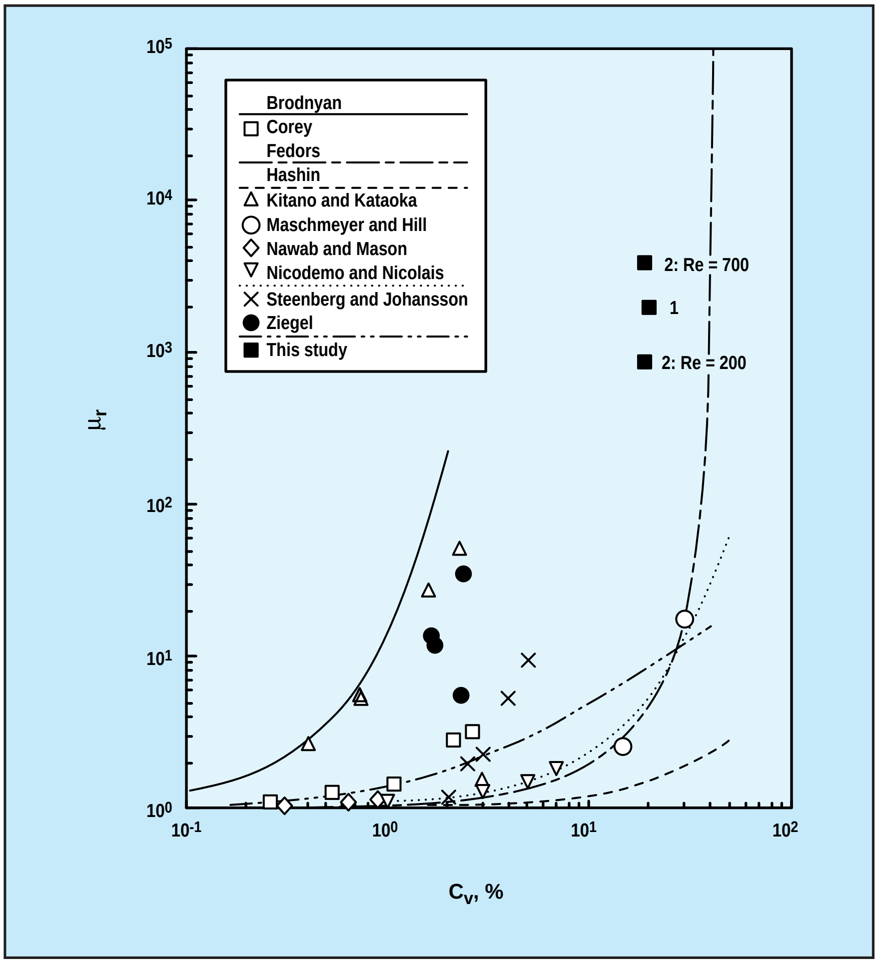
The criterion chosen by Gullichsen and Harkonen (7)—that of turbulent motion throughout the vessel—was used for the onset of fluidization. This was determined from videotapes made of each test. The net torque and rotor speed were then determined from data records made during the test.

The gap size between the rotors and housing was varied between 65 and 5 mm. Even the smallest gap created a strong radial shear gradient which produced a radial gradient in ε_F. To obtain a local value of ε_F, we obtained a correlation for our data as a function of the chamber dimensions:

$$\varepsilon_F = 4.5 \times 10^4 C_m^{2.5}(D_T/D)^{-2.3}; \quad 1.3 \le D_T/D \le 3.1; 1.0 \le C_m; \% \le 12.6 \qquad (4)$$

where D_T is the diameter of the housing, D is the diameter of the rotor, and C_m is the mass concentration, in percent. When written in logarithmic form, Eq. 4 has an r^2 value of 0.900. We then extrapolated Eq. 4 to a zero gap size ($D \to D_T$), to obtain:

3. Relative viscosity as a function of volumetric concentration for fibrous suspensions. Equations in the literature: Brodnyan *(13)*, Hashin *(14)*, Ziegel *(15)*, Nicodemo and Nicolais *(16)*, and Fedors *(17)*. Experimental data for fiber suspensions: Ziegel *(15)*, Nicodemo and Nicolais *(16)*, Nawab and Mason *(18)*, Steenberg and Johansson *(19)*, Corey *(20)*, Maschmeyer and Hill *(21)*, and Kitano and Kataoka *(22)*. The estimates made for a semibleached kraft (SBK) pulp in this study are included: (1) C_m = 10% SBK using the power dissipated at the onset of fluidization and the suspension yield stress; (2) C_m = 9.7% SBK using the power number–Reynolds number relationship for Newtonian fluids.



$$\varepsilon_F = 4.5 \times 10^4 C_m^{2.5} \qquad (5)$$

Estimation of apparent viscosity

Energy dissipation is proportional to both the fluid viscosity and shear rate, G. In laminar flow, $G = dU/dy$ where U is the mean flow velocity and y is the distance over which shear occurs. Here energy dissipation is given by:

$$\varepsilon = \mu G^2 = \mu(dU/dy)^2 \qquad (6)$$

In turbulent flow, the local shear rate is given by $G = u'/\lambda_g$ where u' is the root-mean-square of the fluctuating component of velocity and λ_g is the lateral spatial dissipation scale—the distance over which the velocity fluctuations occur. For isotropic turbulence, energy dissipation is given by Hinze *(9)*:

$$\varepsilon = 15\mu(u'/\lambda_g)^2 \qquad (7)$$

In our case, we are in the transition regime between laminar flow and fully developed isotropic turbulence. We assume that fluidization occurs when the local shear stress is everywhere equal to the yield stress of the pulp suspension; i.e., where:

$$\tau_y = \mu_a G \qquad (8)$$

Here μ_a is the apparent viscosity of the suspension. Following Wahren, we assume that fluidization involves rupture of the fibrous network on a local scale, and that we can represent the level of local shear required to accomplish this by Eq. 6. Accordingly, we obtain:

$$\varepsilon_F = \tau_y{}^2/\mu_a \qquad (9)$$

We employed Eq. 6 rather than Eq. 7 because isotropic turbulence clearly did not exist in our tests at the onset of fluidization.

Using Eq. 9, an estimate of the apparent viscosity of a SBK pulp suspension at the onset of fluidization can be found from measured values of ε_F and τ_y, where ε_F is given by Eq. 5 and τ_y by Bennington *et al. (10).*

$$\tau_y = 8.2C_m{}^{2.8} \qquad (10)$$

Solving for μ_a, we find that:

$$\mu_a = 1.5 \times 10^{-3} C_m{}^{3.1};\ 1 < C_m;\ \% \le 12.6 \qquad (11)$$

Power number comparison

To verify that pulp flow is behaving as a fluid in a turbulent state, we characterized the rotary shear tester as a mixer. For viscous fluids, mixers can be characterized by a power number–Reynolds number relationship. The power number, N_P, is given as:

$$N_P = P/(D^5N^3\rho) \qquad (12)$$

and is commonly plotted as a function of the rotor Reynolds number

$$Re = D^2N\rho/\mu \qquad (13)$$

The N_P – Re relationship for our concentric cylinder shear tester was determined for configurations *A* and *C* using several Newtonian fluids of increasing viscosity [(water, water/glycerol solutions, Shell Omala 1000 (a paraffinic hydrocarbon lubricant), and Dow Corning 200 Fluid (a dimethyl siloxane polymer)]. The curves, shown in **Fig. 2**, are similar to those found for other mixers, namely, a laminar regime where $N_P \propto Re^{-1}$ at low Re, a transition regime, and a turbulent regime where N_P is independent of Re at high Re *(11, 12)*. For the rotor-housing configurations examined here, the beginning of the transition to turbulence occurs over a range in Reynolds number from 200 to 700.

In our tests with pulp suspensions, the measured power numbers in the fluidized regime were found to be identical to those measured for water in the turbulent regime. For example, mixing water in mixer configuration *B* gave $N_P = 3.4 \pm 0.6$. For fluidized suspensions in the same rotor/housing configuration, $N_P = 3.4 \pm 0.5$. This confirms that the fluidized pulp suspensions did indeed behave as a turbulent viscous fluid.

Comparisons with past work

Estimates of suspension viscosity can be made using the methods described earlier. From Eq. 11, the apparent viscosity of a SBK suspension at 10% consistency was found to be 1.9 Pa·s. This is approximately 2000 times greater than that of water. It is compared with other published experimental data and theoretical predictions as shown in **Fig. 3**. Here suspension viscosities are expressed as relative viscosities, μ_r—a dimensionless quantity calculated by dividing the viscosity of the suspension by that of the suspending medium. Fiber concentrations are given by the volumetric concentration, C_v. For pulp fiber suspensions, C_v is greater than C_m due to fiber swelling. A typical bleached kraft pulp having a mass concentration of 10% would have a volumetric concentration of approximately 20%. In Fig. 3, we see that only Maschmeyer *(21)* has measured relative viscosities for fiber suspensions at volumetric concentrations approaching those of the medium consistency pulp suspensions studied here. However, while our estimated viscosities are much higher than Maschmeyer's values, they are consistent with theoretical estimates made by Fedors *(17)*. Note also that extrapolation of measurements made at lower volumetric concentrations could easily fall within the range we have calculated here.

An estimate of the apparent viscosity can also be made using the N_P – Re curves given in Fig. 2. In the laminar regime, there is a unique value of power number that corresponds to each Reynolds number. However, in the turbulent regime, this dependence of the power number and Reynolds number becomes indeterminant due to Reynolds number similarity. The transition point between the two regimes corresponds to the onset of fluidization in our case. Consequently, this point may be used to establish a maximum apparent viscosity for the suspension. This estimate was made for a series of tests conducted using the 100 mm rotor and a gap width of 50 mm (Configuration *A* in Table I). For a C_m = 9.7% (C_v = 18.5%) SBK suspension, the estimated greatest viscosities range from 0.87 (Re = 200) to 3.9 Pa·s (Re = 700) depending on the Reynolds number chosen for the onset of turbulent flow. These are also shown in Fig. 3. The value found from energy dissipation (1.9 Pa·s) falls within this range.

Lastly, we may use our calculated dependence of suspension viscosity on concentration (Eq. 11) to modify Wahren's predictions for ε_F (Eq. 2). Doing this, we find that:

$$\varepsilon_F = 7.7 \times 10^3 C_m{}^{2.2} \qquad (14)$$

which is similar to our finding. Thus it appears that Wahren's prediction of an overly high dependence of ε_F on C_m is due to the use of a water viscosity rather than the suspension viscosity.

Summary and conclusion

Fiber suspensions can display fluid-like behavior that may justifiably be called fluidized under certain circumstances. This occurs in a turbulent regime and, in this state, the suspension can be assigned a viscosity and otherwise follows the laws of fluid mechanics. A useful criterion for the onset of this state is a required level of power dissipation per unit volume, ε_F. For a SBK suspension, this is given by:

$$\varepsilon_F = 4.5 \times 10^4 C_m^{2.5}$$

where C_m is the fiber mass concentration. The apparent viscosity of the suspension also strongly depends on the suspension mass concentration. For SBK, the relationship is:

$$\mu_a = 1.5 \times 10^{-3} C_m^{3.1}$$ TJ

Nomenclature

- C_m = mass concentration, %
- C_v = volume concentration, %
- D = rotor diameter, m
- D_T = housing diameter, m
- G = shear rate, s^{-1}
- N = rotational speed, s^{-1}
- N_p = power number, $P/(D^{5i}N^3\rho)$
- P = power, W
- Re = Reynolds number, $D^2N\rho/\mu$
- ε = power dissipation, W/m^3
- ε_F = power dissipation at point of fluidization, W/m^3
- u = fluctuating velocity, m/s
- u' = root-mean-square turbulence velocity component, m/s
- U = mean velocity, m/s
- λ_g = lateral spatial dissipation scale, m
- μ = viscosity, Pa·s
- μ_a = apparent viscosity, Pa·s
- μ_r = relative viscosity, μ/μ_s
- μ_s = viscosity of suspending medium, Pa·s
- ρ = density, kg/m^3
- τ = local shear stress, Pa
- τ_y = suspension yield stress, Pa

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Received for review Oct. 25, 1994.

Accepted Dec. 13, 1994.