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STUDIES OF SMALL PARTICLE SUSPENSIONS FOR L. M. F. R. PART III – CORRELATION OF HORIZONTAL SETTLING VELOCITIES

by

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SUMMARY

The available experimental data for the horizontal settling velocities of suspensions with particles of small size have been collected. These have been compared with the velocities calculated from the several equations existing in the literature for predicting horizontal settling velocities. No consistent agreement between the experimental and calculated velocities has been found.

Using the effective density ratio, defined as the ratio of the difference in density between solid and liquid to the density of the liquid, the experimental values have been correlated satisfactorily. Further data are needed before a generalised correlation for suspensions can be established.

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1. INTRODUCTION

Experimental work has been in progress for 12 months on the fluid dynamics of suspensions with particles of small size and high density. The experimental information is being obtained using suspensions simulating those likely to be used for the L.M.F. suspension type reactor.

Suspensions of tungsten powder in water (2), and precipitated barium sulphate in water (3), have been pumped to simulate conditions for the systems U–Na and UBe_{13}– Na respectively. Suspensions of red lead in water have been pumped also, to provide settling velocity data in the intermediate density range.

In the literature experimentally determined horizontal settling or suspending velocities are available for only a few suspensions with particles of small size. Small sized particles are defined here as particles which have a distribution with 85 percent by weight of the particles having diameters no greater than 80 microns. The systems with particles of small size studied previously are UO_2–NaK (1), lime–water (11) and ThO_2–water (8). Several empirical equations are available also in the literature for predicting horizontal settling, suspending or transport velocities.

This report deals with one aspect of the simulated suspension work and compares the calculated settling velocities using the existing equations, with experimentally determined settling velocities. An attempt is made to correlate the experimental values in terms of the effective density ratio, defined as the ratio of the difference in density between solid and liquid to the density of the liquid.

2. PARTICLE SIZE

The equations from the literature usually have been derived for particles of uniform size and shape. In most suspensions there is a wide particle size distribution and the particle shape varies. Often it is not possible to evaluate even the largest particle diameter present. The particle size distribution itself will vary with the method of particle size analysis used, for example, there is no correlation between microscopic counting and sedimentation techniques of size analysis for particles less than 20–30 microns.

It is considered that the particle size distributions obtained by a sedimentation technique, giving Stokes' diameters, in the fluid to be used in the pumping experiments more likely approach those actually present in the pumped circuit. These have been used where available. However, the effect of agglomeration on the particle size distribution, as noticed by Abraham et al (1) at 500°C with the UO_2–NaK system is unknown. The de–agglomerating effect of circulation through pumps and fittings is unknown also. No method is available at the present time for determining particle size distributions during circulation.

For the purposes of comparison with the existing equations for horizontal settling velocities, both the 85 percent and 50 percent undersize diameter have been used as suggested by Spells (11). These are designated as d_{85} and d_{50} respectively. The selection of these diameters is purely arbitrary and there may be a better mean effective diameter to use. Since the sphericity of the particles in the suspensions is unknown, no correction can be made for particle shape. As the surface properties of the various solid particles considered are unknown also, the effect of particle wettability cannot be determined.

3. EXPERIMENTAL HORIZONTAL SETTLING VELOCITIES

Table I gives the data available for horizontal settling velocities for suspensions with particles of small size.

Particle size analyses of the tungsten and barium sulphate were obtained using the Andreasen sedimentation technique with water as the suspending medium.

The lead oxide-water settling velocity data were obtained with the apparatus described in reference (3). Particle size analysis of the lead oxide using the Andreasen pipette was not possible because of irreproducibility. The dry powder, however, was 95 percent by weight less than 325 mesh (Tyler) wet screened.

Particle size analysis of UO_2 shown in Table I were obtained using a sedimentation technique (1) with radio-activated UO_2. The suspending medium used is not reported by Abraham et al, and the original reference is unavailable at the present time (7).

The method of particle size analysis used for the lime is not reported by Spells (11). The thoria particle size analysis was made "by a modified pipette method using a centrifugal field to produce sedimentation instead of a gravitational one" (9). The suspending medium was water with Calgon as a dispersing agent.

4. COMPARISON WITH LITERATURE EQUATIONS

(a) Davis' Equation

Davis (5) defined an initial mixing velocity as the velocity at which particles commence to be taken up in suspension by a clear fluid passing horizontally over them. For a spherical particle he derives:-

$$U_o = 6.55 \sqrt{\frac{(\sigma - \rho)}{\rho} d} \qquad (1)$$

where U_o = the initial mixing velocity, ft/sec.

σ = specific gravity of particle

ρ = specific gravity of fluid

d = particle diameter, feet

Table II compares the calculated velocity from equation (1) with the experimental values. The agreement is poor.

(b) Dallavalle Equation

Dallavalle (4) has given an equation for the transport velocity of cinders, carbon, anthracite and quartz in air for horizontal flow. The maximum particle specific gravity was 2.65, giving a density ratio of 2200 to 1, and the particle sizes varied from 0.04 to 0.16 inches.

$$V = 6000 \left(\frac{\rho}{\rho+1}\right) d^{2/5} \qquad (2)$$

where V = transport velocity, ft/min.

ρ = specific gravity of solid

d = diameter of the largest particle, inches

Using the 85 percent undersize and 50 percent undersize particle diameters equation (2) gives the velocities shown in Table III.

The agreement between calculated and experimental velocities is again poor.

(c) Equation of Durand and Condolios

Durand and Condolios (6) have given the following equation for estimating the limiting velocity for deposition of solids in water: –

$$V_L = F_L \sqrt{2gD \frac{(\rho' - \rho)}{\rho}} \qquad (3)$$

where V_L = limiting velocity, ft/sec

F_L = constant depending only on concentration and size of the particle

g = acceleration due to gravity, 32.2 ft/sec^2.

D = pipe diameter, feet

ρ' = specific gravity of solid

ρ = specific gravity of water

This equation is not applicable to all the water systems available since useful values of the constant F_L are not given by Durand and Condolios for sizes below 50 microns.

(d) Equation of Newitt et al

Newitt et al (10) have given an equation for calculating the velocity at which the transition between their "heterogeneous" suspension and "homogeneous" flow occurs. The equation is: –

$$V_H^3 = 1800 \; gDW \qquad (4)$$

where V_H = transition velocity, ft/sec.

g = acceleration due to gravity, 32.2 ft/sec^2

D = internal diameter of pipe, ft.

W = experimental particle terminal velocity, ft/sec.

The authors give another equation for the transition velocity between flow by saltation or a sliding bed and as a heterogeneous suspension. This is: –

$$V_B = 17\,W \qquad (5)$$

where V_B = transition velocity, ft/sec.

W = experimental particle terminal velocity, ft/sec.

Table IV gives the results of the comparison between the calculated velocities from equation (4) and the experimental velocities. There is no agreement. As experimental terminal velocities are unavailable for the systems considered, they were calculated. Horizontal settling velocities calculated from equation (5) resulted in no agreement also.

(e) Spells Correlation

Spells (11) attempted to correlate a minimum velocity, defined as the lowest velocity below which turbulence is insufficient to maintain all the particles in suspension, in terms of a modified Froude Number and the Reynolds number. He assumed that:-

$$\frac{V_m^2}{gd} \cdot \frac{\rho}{(\sigma - \rho)} = \phi\left(\frac{DV_m\,\rho'}{\mu}\right)$$

where V_m = minimum velocity, ft/sec.

g = acceleration due to gravity, 32.2 ft/sec^2

d = particle diameter, feet

ρ = density of medium, lb/cu.ft.

σ = density of solid, lb/cu.ft.

D = internal diameter of pipe, feet

ρ' = Density of slurry, lb/cu.ft.

μ = suspension viscosity (taken by Spells as equal to the medium viscosity). lb/(ft)(sec.)

Table V shows the calculated data for the Spells type correlation and figure (1) plots the results. There is no agreement between Spells' line shown in figure (1) and the systems studied here. However, some improvement could be expected if the suspension viscosity were used in the Reynolds number. This is difficult to attempt since other workers do not give sufficient details to evaluate accurately the suspension viscosity.

Attempts to improve Spells correlation using the particle Reynolds number were made. The data were recalculated replacing the pipe diameter in the Reynolds number with both d_{85} and d_{50}, but no improvement in the correlation was obtained.

(f) New Method of Correlation

If the data shown in Table I are plotted as effective density ratio, $(\sigma - \rho) / \rho$, versus horizontal settling velocity, the line shown in figure (2), can be drawn. This infers that particle size distribution has little effect on the settling velocity and that for suspensions with particles of small size, the horizontal settling velocity is determined by the effective density ratio.

If the data of Hitchon for the settling velocity of ThO_2 in water is omitted, the correlation is improved. Concerning Hitchon's work, it is considered that the settling velocity he determined was not the velocity at which settling on the bottom of the pipe first occurred, and it is felt that the value of 1.4 feet per second is low. This is because the radiometric method of determining the point of settling consisted of setting the scanning unit above the bottom of the pipe, not at the bottom of the pipe. Also, the use of a stainless steel pipe and the rather large collimating slit of 1/8 inch on the thulium 170 source side of the traversing gear would not enable the velocity at which settling first occurred to be detected.

Considerably more experimental data are needed to determine the limitations of the plot shown in figure (2).

5. FURTHER WORK

Further work would have to cover: -

(a) Experimental determination of the effect of different diameters on the horizontal settling velocity.

(b) Experimental determination of the effect of concentration on the horizontal settling velocity.

(c) Modification of the Spells correlation to include effects of viscosity and concentration of suspension.

(d) Further calculations using the particle Reynolds number.

This work should provide the additional data required to provide a generalised correlation for suspensions.

6. ACKNOWLEDGMENTS

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TABLE I

EXPERIMENTAL DATA ON HORIZONTAL SETTLING VELOCITIES

System	Mean Temp °C	Particle Diameter Microns		Particle Density g/cc	Pipe Internal Diameter Inches	Experimental Horizontal Settling Velocity ft/sec.
		d_{85}	d_{50}			
$W-H_2O$ (2)	43	12.5	3.6	19.3	1.0	2.6
$BaSO_4-H_2O$ (3)	35	35	30	4.5	1.0	1.6
$Pb_3O_4-H_2O$	37	–	–	9.1	1.0	2.2
UO_2–NaK (1)	25	3.5	2	10.79	0.44	2.1
UO_2–NaK (1)	450	3.5	2	10.79	0.44	2.4
Lime–Water (11)	–	80	56	2.0	4.0	0.9
ThO_2–Water (8)	–	–	2.7	9.69	–	1.4

TABLE II

COMPARISON WITH DAVIS (5) EQUATION

System	Mean Temp °C	σ	ρ	$\frac{(\sigma - \rho)}{\rho}$	Calculated U_o ft/sec.		Experimental ft/sec.
					$d = d_{85}$ feet	$d = d_{50}$ feet	
$W-H_2O$	43	19.3	1.0	18.3	0.18	0.096	2.6
$BaSO_4-H_2O$	35	4.5	1.0	3.5	0.13	0.12	1.6
$Pb_3O_4-H_2O$	37	9.1	1.0	8.1	–	–	2.2
UO_2–NaK	25	10.79	0.86	11.5	0.075	0.057	2.1
UO_2–NaK	450	10.79	0.76	13.2	0.081	0.061	2.4
Lime–Water	–	2.0	1.0*	1.0	0.11	0.089	0.9
ThO_2–Water	–	9.69	1.0*	8.7	–	0.058	1.4

* Assumed temperature was 20° C.

TABLE III

COMPARISON WITH DALLAVALLE (4) EQUATION

System	Calculated V ft/sec.		Experimental ft/sec.
	$d = d_{85}$ inches	$d = d_{50}$ inches	
$W-H_2O$	4.5	2.8	2.6
$BaSO_4-H_2O$	5.9	5.5	1.6
UO_2-NaK	2.6	2.1	2.1 - 2.4
Lime-Water	6.7	5.8	0.9
ThO_2-Water	-	2.3	1.4

TABLE IV

COMPARISON WITH EQUATION (4) OF NEWITT ET AL (10)

System	Terminal velocity W ft/sec.		Calculated V_H ft/sec.		Experimental Velocity ft/sec.
	d_{85}	d_{50}	d_{85}	d_{50}	
$W-H_2O$	0.0082	0.00068	3.4	1.5	2.6
$BaSO_4-H_2O$	0.0106	0.0078	3.7	3.4	1.6
UO_2-NaK, 25°C	0.00029	0.000095	0.9	0.6	2.1
UO_2-NaK, 450°C	0.00107	0.00035	1.3	0.9	2.4
Lime-Water *	0.0114	0.0056	6	4.8	0.9

* Assumed temperature was 20° C.

TABLE V

CALCULATED DATA FOR THE SPELLS (11) CORRELATION

System	Modified Froude No. $\frac{V_m^2}{gd} \cdot \frac{\rho}{(\sigma - \rho)}$		Reynolds No. $\frac{DV_m \rho'}{\mu}$
	$d = d_{85}$	$d = d_{50}$	
$W-H_2O$	278	970	34,000
$BaSO_4-H_2O$	196	229	19,000
UO_2–NaK, 25°C	1040	1810	12,300
UO_2–NaK, 450°C	1180	2070	47,000
Lime–Water*	96	137	28,900

* Assumed temperature was 20°C.

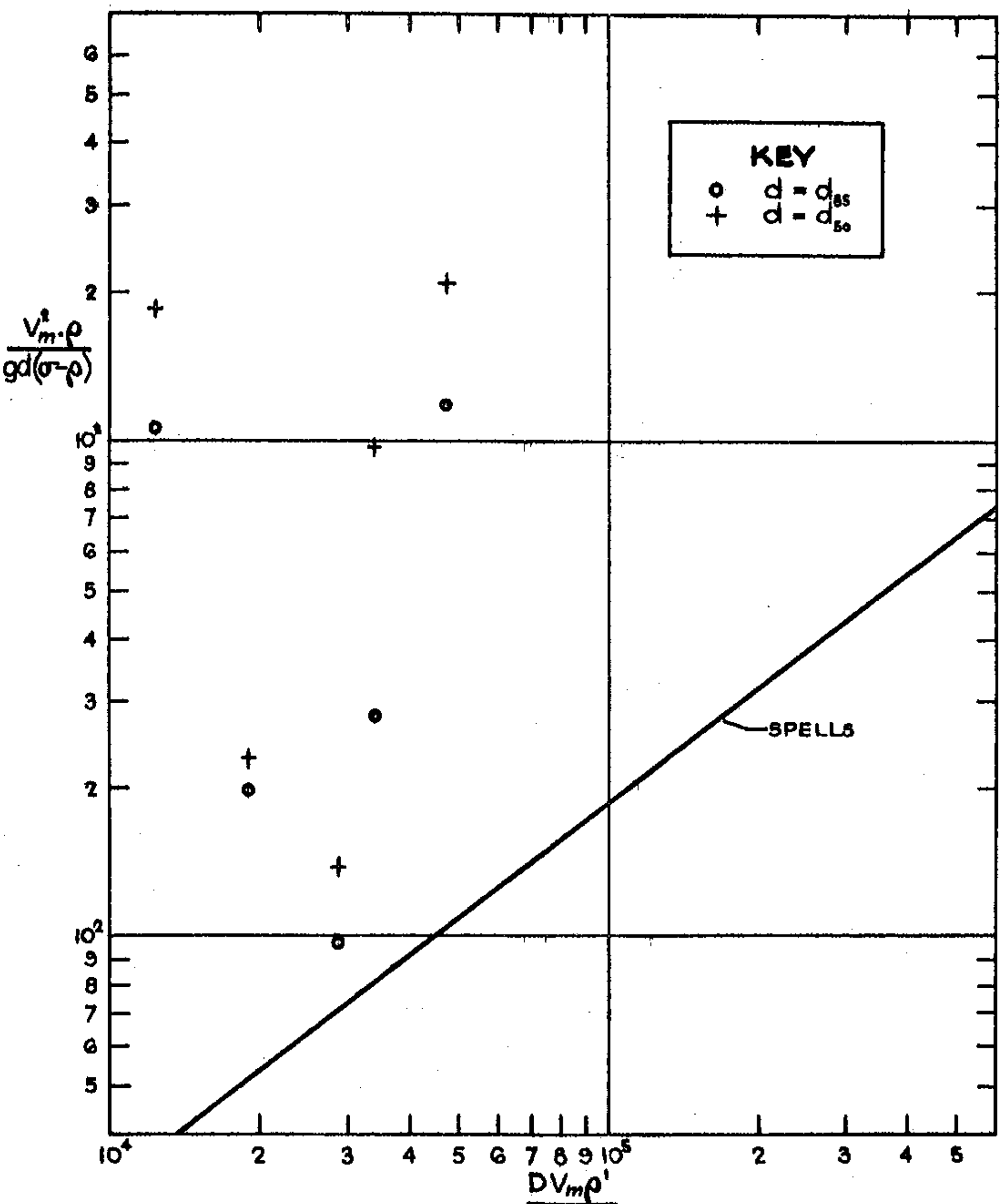

FIGURE 1 :
Froude Number vs Reynolds Number plot for Spells' correlation.(11)

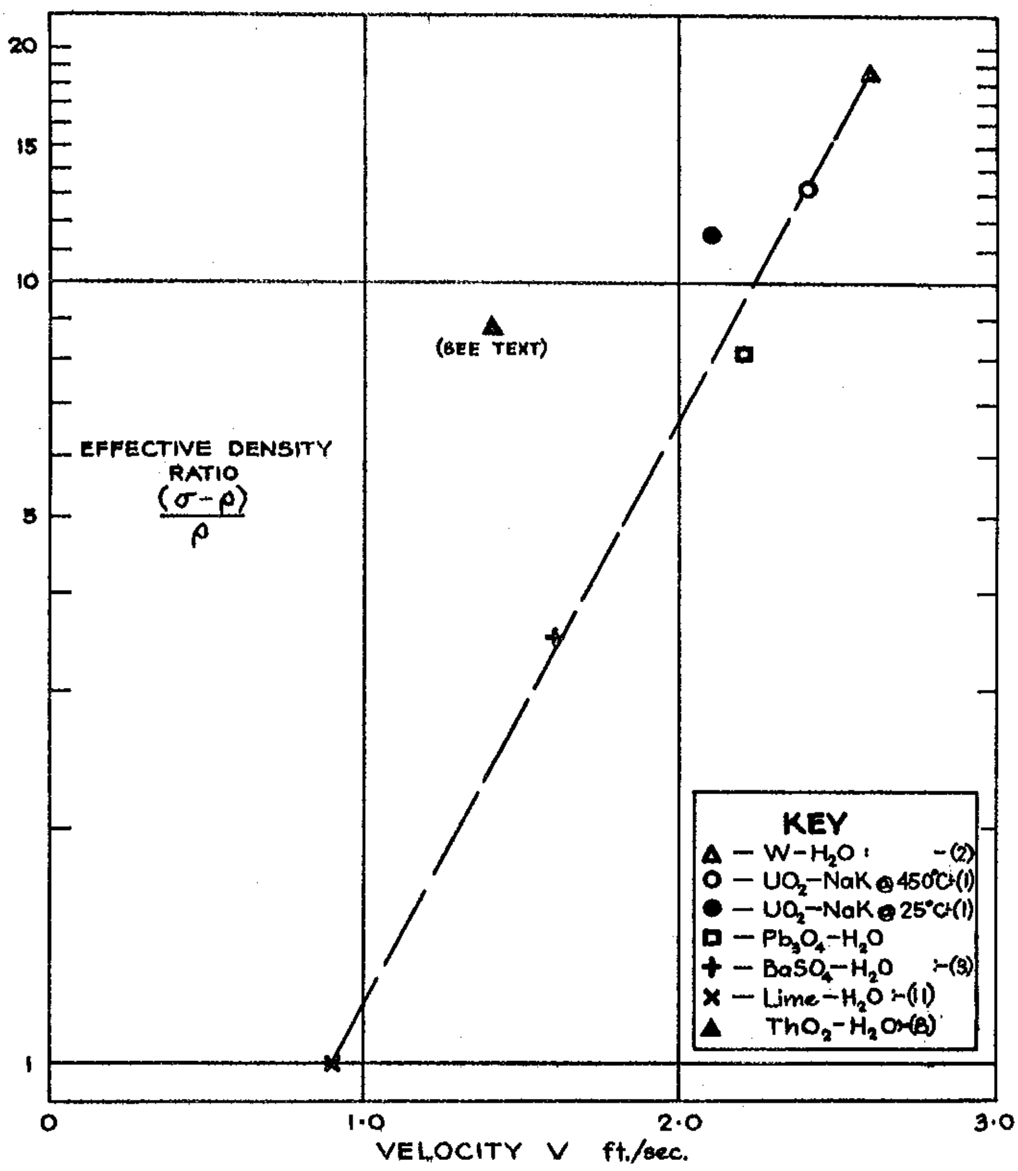

FIGURE 2 :
Effective Density Ratio vs Horizontal Settling Velocity for small particle suspensions.