OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

EXTERNAL TRANSMITTAL AUTHORIZED

ORNL

CENTRAL FILES NUMBER

58-5-116

MASTER

DATE: May 1, 1958

COPY NO. 109

SUBJECT: Relation Between Hindered Settling
Rate and Viscosity of Thorium Slurries

TO: D. E. Ferguson

FROM: J. M. DallaValle
 C. F. Bishop

ABSTRACT

The hindered settling rate, u_0 , of an aqueous thorium oxide suspension (≤ 700 g Th/kg H_2O) is related to Stokes' settling rate, u_s , by the equation

$$u_s/u_0 = 9.4 (1 - \epsilon)/\epsilon^3$$

where ϵ is the void fraction and $(1 - \epsilon)$ the volume fraction of solids. A similar expression should hold between the viscosity of the water and the slurry viscosity. Viscosity measurements from room temperature to $100^\circ C$ on 200 to 700 g Th/kg H_2O slurries of thorium oxide calcined from 1000 to $1600^\circ C$ indicate that such a relationship does apply.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

1.0 INTRODUCTION

The measurement of thorium-water slurry viscosities at high temperatures is complicated and difficult. Suitable methods capable of exceeding 200°C have yet to be devised which have proved satisfactory. Thomas¹ has designed a convenient bench type apparatus, but a successful stirring mechanism to maintain a homogeneous slurry has not yet been obtained. Kitzes and Crowley² made numerous measurements (up to 200°C) with rather large autoclaves connected by a capillary. The apparatus could not be used with any suitable degree of accuracy. Plugging of the rather long capillary was frequent and each run a time-consuming operation.

It is well established that hindered settling rates, when known at one temperature, can be extrapolated to any other temperature with surprising accuracy.³ Moreover, techniques for measuring hindered settling rates are rather easy to apply. It would, therefore, be advantageous to determine whether any correlation exists between the rate of hindered settling and slurry viscosity. If a correlation can be found for a variety of concentrations over a moderate range of temperatures, it might well be supposed that the correlation could be extended to higher temperatures.

There are two reasons for assuming that a correlation between hindered settling rate and slurry viscosity exists. The first is intuitive and follows repeated observations that thick suspensions settle more slowly than less concentrated suspensions. Thus, since the rate of settling depends upon all physical and fluid properties of the particles and liquid, an inverse relationship between settling rate and measured viscosity might be found which would be of great generality. The second approach hinges on the observation that the hindered settling rate, u_0 , is related to the Stokes' settling rate, u_s , by the factor

$$u_s/u_0 = 9.4 (1 - \epsilon)/\epsilon^3 \quad (1)$$

where ϵ is the void fraction and $(1 - \epsilon)$ the fraction of solids.

Actually, the hindered settling rate of a dispersed material having a wide size-spectrum is faster than for Stokes' settling of a single particle having the same average diameter. In fact, as may be seen from equation (1), the hindered settling rate and the Stokes' settling rate are equal when

$$\epsilon^3/(1 - \epsilon) = 9.4 \quad (2)$$

which occurs for thoria at concentrations of approximately 700 g Th/kg H₂O. At higher concentrations, $u_0 < u_s$. Curiously, the critical concentration of 700 g is about the concentration at which "compaction" settling begins.

The term to the right of equation (1) may be regarded as a viscosity correction term of Stokes' settling in terms of hindered settling rate, all other terms constant, or as a mean particle diameter correction to be used to equalize the hindered and Stokes' settling rates, other things equal. The first is equivalent to saying that

$$\eta = 9.4 \mu (1 - \epsilon)/\epsilon^3 \quad (3)$$

where μ is the true fluid viscosity and η the apparent viscosity of the slurry.

While equation (3) would appear to make the value of η less than μ , which is contrary to observations, it does seem worthwhile to investigate the usefulness of the relation as a method of empirical correlation.

2.0 METHOD OF STUDY

2.1 Hindered Settling

D-16 and CB thoria series fired at 1000, 1300 and 1600°C were used in the tests. Concentrations of thoria equivalent to 200, 400, 500 and 700 g Th/kg H₂O were prepared and hindered settling rates determined in the usual manner at room temperature. Settling rates at temperatures higher than 25°C were not made since, as indicated above, the method of predicting settling rates at any other temperature is well known.³

2.2 Viscosity Measurements

The slurry viscosities were determined for different concentrations at temperatures between 1 and 95°C. A stainless steel capillary 20 cm in length and 0.089 cm internal diameter was used. The arrangement is shown in Fig. 1. A slurry of a desired particulate concentration was prepared and placed in a 400 ml stainless beaker provided with a stirrer. The container was placed in a constant temperature bath and stirred until the desired temperature was reached. The flow

Fig. 1. Viscometer for Determining Viscosities of Slurries
from 0 to 100°C

was then initiated by application of suction to a receiver shown to the right of the insulated capillary tube. This receiver consisted of two bulbs in series; one calibrated to hold 50 ml and the other 60 ml. The upper portion of the receiving column was equipped with a reflux condenser since often---at temperatures above 90°C---the applied suction to the receiver column would cause boiling.

The flow through the capillary was initiated by applying a negative pressure to the receiver. The time to fill either the 50 ml or 60 ml burette (or both) was observed for a fixed negative pressure. By varying the pressure, different rates of flow could be measured and from both observations it was possible to obtain the viscosity of the slurry at the fixed temperature as follows:

The Poiseuille equation can be written as

$$\dot{R}/g_c S = \eta^{-1} \quad (4)$$

where $\dot{R}$ is the rate of shear

$$\dot{R} = 32V/\pi D^3$$

V being the volume rate of flow and D the capillary diameter, and

$$S = D \cdot \Delta p / 4L$$

where S is the stress, Δp the pressure drop across the capillary of length L.

On the experiments described, Δp was measured with a mercury U-tube and the displacement observed in cm Hg was converted to g/cm².

We see, therefore, that a plot of $\dot{R}$ vs S, if it results in a straight line, will have a slope whose value will be g_c/η , g_c being a unit conversion factor (gravitational acceleration constant).

In all, approximately forty slurries were studied. Except for some 1600°C fired CB material, all behaved as Bingham plastics with relatively low initial stresses. Some high fired materials behaved erratically probably due to the presence of large agglomerates.

3.0 RESULTS

3.1 Hindered Settling - Viscosity Relation

Figure 2 shows the relation between the observed viscosity of a slurry expressed by equations (1) and (3), i.e.,

$$u_s/u_o = \eta/\mu = 9.4 (1 - \xi)/\xi^3$$

with $\mu = 1$. If this relation applies, it would be expected that a plot of the observed viscosity against u_s/u_o would result in a straight line. That such is the case is shown in Fig. 2. However, the line does not pass through the origin as expected. The points represent averages of the observed viscosities. The lowest point to the left is the average of more than 10 samples which did not vary more than ± 2 cp and can hardly be in error while the upper right hand point represents concentrations of 700 g Th/kg H₂O and is average of 4 samples of the D-16 series. The equation of the straight portion of the line in Fig. 2 is

$$\eta_{25^\circ\text{C}} = 1.09 + u_s/u_o \quad (5)$$

3.2 Temperature-Viscosity Relation

Figure 3 is a plot of the relative slurry viscosity (observed viscosity at temperature to viscosity observed at 25°C, $\eta_T/\eta_{25^\circ\text{C}}$) vs reciprocal absolute temperature. The data plot as a straight line on semi-log grid according to the equation

$$\eta_T = 1.52 \times 10^{-2} \eta_{25^\circ\text{C}} e^{-1.25 \times 10^3/T} \quad (6)$$

Thus, equations (5) and (6) permit the determination of slurry viscosity in terms of the function $\phi = 9.4 (1 - \xi)/\xi^3$,

$$\eta_{25^\circ\text{C}} = 1.09 + \phi$$

and temperature. It is presumed, of course, that these equations apply to thorium slurry concentrations between 200 and 700 kg Th/kg H₂O and can be extended to temperatures up to 300°C. Figure 4 illustrates the calculations for a slurry of 500 g Th/kg H₂O.

UNCLASSIFIED
ORNL-LR-Dwg. 29653

Fig. 2. Relation Between Slurry Viscosity at 25°C and the Ratio of Stokes Velocity and Hindered Settling Velocity, u_s/u_o

UNCLASSIFIED
ORNL-LR-Dwg. 29654

Fig. 3. Relative Slurry Viscosity, η_T/η_{250C} , Versus Reciprocal Absolute Temperature

UNCLASSIFIED
ORNL-LR-Dwg. 29655

Fig. 4. Thorium Oxide Slurry Viscosity Versus Reciprocal Absolute Temperature; 500 g Th/kg H₂O

REFERENCES

1. D. G. Thomas and T. M. Gayle, "The Rheology of Thorium Oxide Slurries," ORNL CF-55-10-73, October 17, 1955.
2. P. R. Crowley, "Homogeneous Reactor Project Quarterly Progress Report October 31, 1955," ORNL-2004, p. 69.
3. J. P. McBride, V. D. Allred, J. M. DallaValle, and R. L. Pearson, "Mass Subsidence of Thoria Slurries at High Temperatures and Pressures," paper delivered at 3rd Annual Meeting of American Nuclear Society, Pittsburgh, Pennsylvania, June 10-12, 1957.

DISTRIBUTION

1. D. E. Ferguson
2. HRP Director's Office
Rm. 259, 9204-1
3. G. M. Adamson
4. S. E. Beall
5. A. M. Billings
6. R. E. Blanco
7. E. G. Bohlmann
8. S. E. Bolt
9. E. S. Bomar
10. J. C. Bresee
11. J. R. Brown
12. K. B. Brown
13. F. R. Bruce
14. W. D. Burch
15. R. H. Chapman
16. R. D. Cheverton
17. H. C. Claiborne
18. E. L. Compere
19. R. S. Crouse
20. F. L. Culler
21. J. S. Culver
22. D. G. Davis
23. R. J. Davis
24. W. K. Eister
25. J. R. Engel
26. J. L. English
27. J. D. Flynn
28. C. H. Gabbard
29. W. R. Gall
30. H. E. Goeller
31. A. T. Gresky
32. J. C. Griess
33. R. S. Greeley
34. P. A. Haas
35. P. H. Harley
36. P. N. Haubenreich
37. J. W. Hill
38. E. C. Hise
39. C. J. Hochanadel
40. G. H. Jenks
41. D. T. Jones
42. S. I. Kaplan
43. P. R. Kasten
44. F. Kertesz
45. J. O. Kolb
46. R. B. Korsmeyer
47. K. A. Kraus
48. C. G. Lawson
49. R. E. Leuze
50. R. B. Lindauer
51. R. A. Lorenz
52. M. I. Lundin
53. R. N. Lyon
54. W. L. Marshall
55. J. P. McBride
56. H. F. McDuffie
57. H. A. McLain
58. R. A. McNees
59. J. R. McWherter
60. R. L. Moore
61. L. F. Parsly, Jr.
62. F. N. Peebles
63. M. L. Picklesimer
64. S. A. Reed
65. D. M. Richardson
66. G. W. Rivenbark
67. R. C. Robertson
68. M. W. Rosenthal
69. H. C. Savage
70. C. L. Segaser
71. E. M. Shank
72. M. D. Silverman
73. M. J. Skinner
74. I. Spiewak
75. R. W. Stoughton
76. J. A. Swartout
77. E. H. Taylor
78. D. G. Thomas
79. D. S. Toomb
80. W. E. Unger
81. R. Van Winkle
82. A. M. Weinberg
83. K. W. West
84. J. C. Wilson
85. C. E. Winters
86. F. C. Zapp
- 87-88. REED Library
- 89-90. Central Research Library
- 91-92. Document Reference Library
- 93-107. Laboratory Records
108. ORNL-RC
- 109-123. TISE, AEC