9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

SHEAR RATE DEPENDENT VISCOSITY OF FLUIDIZED BED

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ABSTRACT

This paper presents the problems in dealing with fluidized bed dynamics - particularly its rheological behaviour. The relations between the shear stress and the shear rate obtained while investigating the fluidized bed definitely indicate its non-newtonian nature. The analysis of the shape of the curves permits one, by considering its rheological behaviour, to classify the bed as a non-newtonian fluid.

The classification of the fluidized bed as a non-newtonian fluid warrants the application of recognized rheological models for its description. The Prandtl's-Eyring's model gives particularly good results in the case of the fluidized bed. The author also presents his own rheological model of the fluidized bed.

THE APPLIED METHOD AND THE INVESTIGATION PROGRAM

The analogies occurring both in the behaviour of the liquid and the fluidized bed suggest that the bed possesses qualities corresponding to viscosity in fluids. The notion of viscosity of the fluidized bed has not been defined in scientific literature but is used here in the form accepted for fluids. By the notion of "the viscosity of the fluidized bed" we understand the viscosity of the "suspension" which is treated as a continuous medium. In the case of a non-newtonian fluid we deal with the apparent viscosity, the value of which changes with the shear rate increase. None of a number of articles on the viscosity of fluidized beds and suggestions concerning its measurement (Binnie, 1963; Grace, 1970; Hagyard, 1966; Ritzman, 1977; Steward, 1968), can be considered satisfactory either because of the conception of the bed adopted or the measurement methods applied. The equations recommended in literature for calculating the viscosity coefficient of the fluidized bed give, in many cases, contradictory and different results.

This article presents generally the problem of the fluidized bed as a system of complex rheological behaviour. The distinctly non-newtonian nature of the suspension of a solid in the fluid whose structure resembles the fluidized bed, and the Kramer's (1951) observation make it possible to propose a hypothesis about the non-newtonian nature of the fluidized bed.

In order to verify this hypothesis the author studied a simple flow developed in a rheometer (Van Waer, 1963). As a result of the nature of the phenomenon of the fluidization it was possible to study only the case of Couette flow in a rotating rheometer. In the case of the investigation of the rheological behaviour of the fluidized bed the direct application of the case of flow between two coaxial rotating cylinders is not possible since the fluidized bed particles are too large in comparison with the axial clearance. Therefore, in the experiments carried out to prove the hypothesis the flow situation in which the cylinder was rotating in an unlimited volume of the fluid was studied. This is a particular case of the flow between two coaxial cylinders in which the radius of the outer cylinder is equal to infinity.

The expression of the shear rate on the surface of the rotating cylinder of the accepted flow model was given by Kriger and Maron (1954). They stated that, in this case, the shear may be calculated from the following equation:

$$\dot{\gamma} = \frac{4\pi n}{r} \tag{1}$$

and the shear stress on the surface of the cylinder is expressed as:

$$\tau = \frac{M}{2\pi H R^2} \tag{2}$$

The dependence of the torque moment M on the angular velocity of the rotating cylinder n should be stated in order to describe the parameter r. On the basis of the results obtained it has been found that the dependence, in the case of the fluidized bed, is shown most precisely by the following equation:

$$M = \frac{n}{An + B} \tag{3}$$

From the above equation the parameter r is obtained:

$$r = \frac{B}{An + B} \tag{4}$$

Substituting this parameter into equation (1) gives the expression for the shear rate in the form:

$$\dot{\gamma} = \frac{4\pi n(An + B)}{B} \tag{5}$$

Fluidization is a very complex phenomenon since the bed is influenced by many factors. From the point of view of their influence on the fluidized bed dynamics the following most important parameters should be mentioned: fluidization number L, particle density of the filling material ρ_p, equivalent diameter of the particles d_p, fluidizing fluid density ρ_l, and the fluidizing fluid viscosity η_l. In the experiments the effect of the influence of the density and viscosity of the fluidizing air on the rheological behaviour of the fluidized bed has been omitted since the fluidizing air density is minimal as compared to the particle density, and its viscosity in relation to the viscosity of the fluidized bed can also be considered to be of little importance. In view of the able only the influence of the fluidization number, the equivalent diameter of the particles and their density were tested. For the detailed investigation of the influence of the fluidization number, a fluidized bed was tested, in which the aloxite used as a filling material had an equivalent diameter of the particles d_p = 141 µm with the following 16 fluidization numbers: L = 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, 4, 4.25, 4.5, 4.75, 5.

The fluidized beds of the aloxite which had the equivalent diameters d_p = 117, 141, 185, 232, 303, 386, 460, 525 µm, were tested for the detailed formulation of the influence of the equivalent diameter of the particles.

Both tests were carried out using constant fluidization numbers L = 2. The fluidized bed of aloxite and quartz sand with the constant equivalent diameter of the particles d_p = 141 µm, and two values of the fluidization numbers L = 1.25 and L = 2.5 were tested in order to estimate the influence of the particle density.

A TEST STAND

In order to carry out the investigation program a test stand was built, the main elements of which were: a fluidization column and a prototype rotating rheometer. A tube of 210 mm inside diameter and 425 mm in length constituted the column. The height of the investigated fluidized bed at rest was equal to 350 mm. The measurement cylinder of the rheometer was placed in the axis of the fluidization column where the influence of the distributor is not visible. The cylinder, 39 mm in diameter and 72 mm high, was made of alloy steel and fixed on the bar 230 mm long in the rheometer head. Longitudinal cuts 0.7 mm deep were made on the surface of the cylinder in order to minimize the slip between the cylinder and fluidized bed. The cylinder reached 25 rotational speeds between 0.0083 and 4.05 s^{-1}.

Quartz sand and aloxite were used as filling material. An equivalent diameter was used to identify the material since the particles of the material had various fractional compositions.

THE RESULTS OF THE STUDIES AND THEIR INTERPRETATION

A knowledge of the variation of torque with the angular velocity of the rheometer is necessary to define the relations between shear stress and the shear rate. As mentioned above the analysis of the shape of the curves obtained made it possible to express them in the form of equation (3). When transformed, the equation assumes a linear form:

$$\frac{n}{M} = An + B \tag{6}$$

The flow curves obtained for the following fluidized beds were chosen to illustrate and exemplify the results obtained: quartz sand with the equivalent diameter of particles d_p = 141 µm at the fluidization number L = 1.25; quartz sand with the equivalent diameter of particles d_p = 141 µm at the fluidization number L = 2.5; and the aloxite with the equivalent diameter of the particles d_p = 141 µm at the fluidization number L = 2.5.

Knowledge of the parameters A and B in equation (6), with application of the relations previously shown, made it possible to calculate the value of the shear stress which occurs on the surface of the measuring cylinder. The sample flow curves are shown in Fig 1.

The analysis of the shape and the nature of the curve confirms that:

a) the fluidized bed behaves like a non-newtonian fluid;
b) characteristic shapes in the succeeding ranges of the shear rate, mentioned by Ostwald (1925), occur on the flow curves, except for the very high shear rates which were not investigated;
c) in the range of small shear rate of the order of 0 to 10 s the shape of the flow curves may be considered to be linear and thus the apparent viscosity in this range may be recognized as constant, and the behaviour of the fluidized bed corresponds to that of newtonian fluids.

The classification of the fluidized bed as a non-newtonian fluid warrants defining its behaviour with the recognized rheological models, such as Ostwald-de Waele, Prandtl-Eyring, Szulman, or Casson (Kemblowski, 1972; Przybylski, 1979). The analysis of usability, which was carried out, proves their aplicability in the studied range of shear rates. In this case

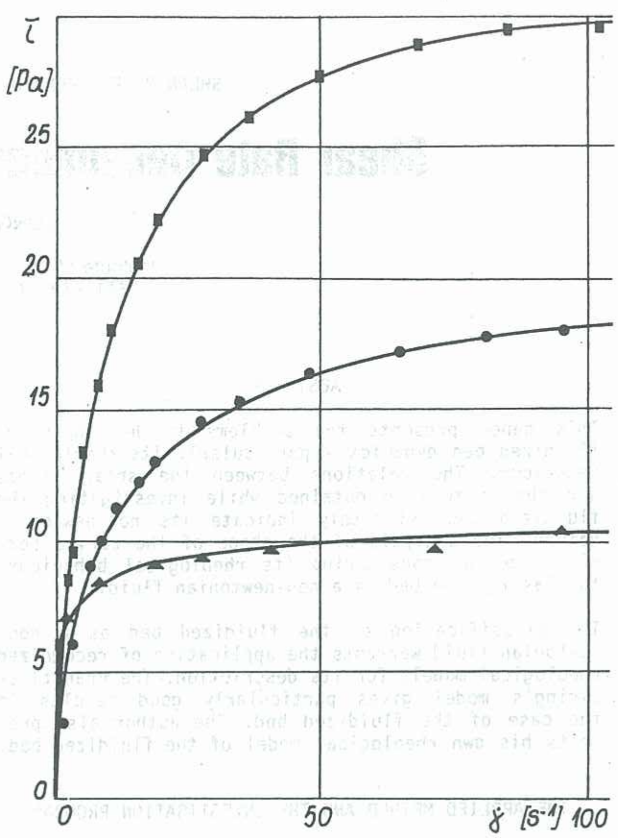

Fig 1: The shear stress as a function of the shear rate.

quartz sand, d_p = 141 µm, L = 1.25
quartz sand, d_p = 141 µm, L = 2.5
aloxite, d_p = 141 µm, L = 2.5

of the fluidized bed the Prandtl-Eyring model gives especially good results. The author has also offered his own rheological model of the fluidized bed in the form of:

$$\tau = \frac{\dot{\gamma}}{a\dot{\gamma} + b} \tag{7}$$

It turned out that it represents the shape of the flow curves much better than previously presented rheological models.

The dependence of the apparent viscosity as a function of shear rate is more useful for practical application than the flow curves. The relationship between the apparent viscosity and the shear rate is expressed by the formula:

$$\eta' = \frac{\tau}{\dot{\gamma}} \tag{8}$$

Making use of this equation one passes from the flow curves to the apparent viscosity curves as a function of the shear rate. The flow curves shown in Fig 1 correspond to the curves of the dependence of the viscosity on the shear rate - the so-called shear curves in Fig 2.

Since lack of space makes it impossible to illustrate all the dependences obtained we will proceed to a recapitulation of the results obtained and their interpretation.

A very strong influence of the fluidization velocity on the apparent viscosity may be observed. The apparent viscosity grows significantly with the increase of the fluidization number eventually rising to a maximum. Such a shape may be interpreted in terms of the internal friction in the fluidized bed which results from particles colliding at random. With the growth of the fluidization velocity the momentum of the particles increases, thus the internal friction increases. On the other hand the viscosity of the fluidized bed decreases with the growth of the fluidization bed density which affects the internal friction adversely. The overlapping of these two effects has the restraining effect on the growth of the viscosity at high fluidization velocities.

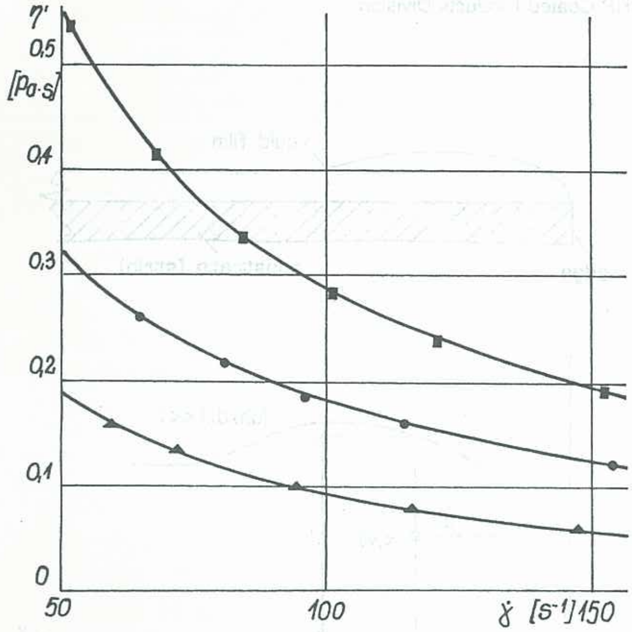

Fig 2: The apparent viscosity as a function of the shear rate.
quartz sand, d_p = 141 µm, L = 1.25
quartz sand, d_p = 141 µm, L = 2.5
aloxite, d_p = 141 µm, L = 2.5

The diameter of the filling material turned out to be the second parameter which affects the apparent viscosity of the fluidized bed. In the range of the particle diameters examined, the apparent viscosity grows and next gently decreases. The continuous increase of the viscosity with the growth of the particle size would result from the accepted model for the fluidized bed internal friction. Therefore there must be some action giving the contrary effect. It seems that gas bubbles occurring in the fluidized bed, the quantity and size of which increase with the growth of the particle diameter, are the cause of this effect. As far as the influence of the particle density on the apparent viscosity is concerned we must state that it is unequivocable. With the growth of the particle density the apparent viscosity of the fluidized bed also grows and this is compatible with the action of the friction.

NOMENCLATURE

d_p - equivalent diameter
H - height of cylinder
$L = U/U_{mf}$ - fluidization number
M - torque moment
n - angular velocity
R - radius of cylinder
U - air fluidizing velocity
U_{mf} - minimum air fluidizing velocity
$\dot{\gamma}$ - shear rate
η' - apparent viscosity of fluidized bed
ρ_p - density of particle
τ - shear stress

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