

Communications to the Editor

On the Calculation of Shear Rate and Apparent Viscosity in Airlift and Bubble Column Bioreactors

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Continuing developments in biotechnology have made available several new biocatalysts—hybridomas, plant cells, and genetically engineered microorganisms—for use in production. Many of these catalytic entities have been demonstrated to be sensitive to shear. In this context, the question of prevailing shear rate, particularly in low-shear bubble column and airlift bioreactors, deserves attention. Furthermore, the associated, unsolved problem of the value of apparent viscosity of a non-Newtonian biofluid in a bioreactor needs some comment in view of the many misconceptions that can be found in the literature. This communication points out some significant disparities in the available shear rate data and discusses the errors in the available methods of estimating the shear rate.

THE SHEAR RATE

As is well known, the effective viscosity for non-Newtonian media following a power law behavior depends on the shear rate ($\dot{\gamma}$):

$$\eta_{\text{eff}} = K\dot{\gamma}^{n-1} \quad (1)$$

In order to calculate the apparent viscosity (η_{eff}), the shear rate in the bioreactor should be known. A commonly used¹⁻⁵ expression for the mean shear rate is

$$\dot{\gamma} = 5000U_G \quad (2)$$

where U_G is the superficial gas velocity. Equation (2) was developed by Nishikawa et al.⁶ for *bubble columns*.

In some recent work,^{4,5} equation (2) has been applied to airlift reactors by replacing U_G with the superficial gas velocity in the riser, U_{GR} . While the use of equation (2) in bubble columns remains questionable (as discussed later in this communication), its extension to airlift devices is quite inappropriate, as explained in the following paragraphs.

Equation (2) was developed for bubble columns and the U_G in it is the superficial gas velocity based on the bubble column cross section. Now the specific pneumatic power input in bubble columns is given by

$$\frac{P_G}{V_L} = \rho_L g U_G \quad (3)$$

which applies when the isothermal expansion of gas is the predominant source of power. In view of what is known⁷ about airlift reactors of the type used, for example, by Popovic and Robinson,^{4,5} we presume that gas expansion was the main contributor to the power supplied in the work reported.^{4,5} Equations (2) and (3) may be combined to give

$$\dot{\gamma} = \frac{5000}{\rho_L g} \left(\frac{P_G}{V_L} \right) \quad (4)$$

which is reasonable, since over some limited range at least, the shear rate should increase with the pneumatic energy input to the fluid. However, equation (4) is valid only for the bubble column configuration. In an airlift reactor the correct power input expression is different, as shown below:

$$\frac{P_G}{V_L} = \rho_L g U_{\text{GR}} \frac{A_r}{A_r + A_d} \quad (5)$$

For the airlifts employed by Popovic and Robinson,^{4,5} the $A_r/(A_r + A_d)$ correction factors would be 0.90 and 0.69 for the airlift reactors with A_d/A_r of 0.111 and 0.444, respectively. Consequently, the expression for the shear rate in the airlift should be

$$\dot{\gamma} = \frac{5000}{\rho_L g} \frac{A_r + A_d}{A_r} \frac{P_G}{V_L} \quad (6)$$

if equation (2) is assumed to apply. Clearly, the use of the same expression [eq. (2)] for bubble columns and airlifts cannot be justified for the simple reason that equal U_G and U_{GR} do not result in equal specific power inputs in these two types of systems. Hence, the level of turbulence and shear rates in them would be different.

Although the reasoning behind equation (5) should be clear, we would nevertheless examine the logic behind this equation because that is where erroneous interpretations have occurred previously. Let us envision a bubble column with gas sparged across its entire cross section. Now we transform this bubble column into a split-cylinder airlift, for example, by insertion of a tightly fitting vertical baffle with width equaling the column diameter. The total gas flow in the transformed vessel is kept the same as in the bubble column with the exception that the gas is now sparged in

the riser section of the airlift. Obviously, the bubble column and the airlift have the same specific power being put into them; however, the U_G (for bubble column) and U_{GR} (for the airlift) are not the same. Exactly the same analogy holds for external-loop airlifts. Thus, the view that $\dot{\gamma}$ is proportional to U_G in one case and to U_{GR} in another is unsound.

The often implied, general applicability of equations such as equation (2), even in bubble columns, is doubtful. Plots of several of the available equations for shear rate in bubble columns are shown in Figure 1 for an air-water system. Perhaps the only common denominator of these equations is the enormous disparity among the predictions of $\dot{\gamma}$. Because the degree of turbulence in a reactor must depend not only on the power input but also on the momentum transport characteristics of the fluid itself (i.e., μ_L and ρ_L) (indeed, it is well known that the bubble size in a turbulent field is dependent not only on power input but also on the viscosity and the density of the fluid), it is reasonable to assume that correlations which express $\dot{\gamma}$ as a function of U_G (or U_{GR}) only are incomplete. The only inference is that

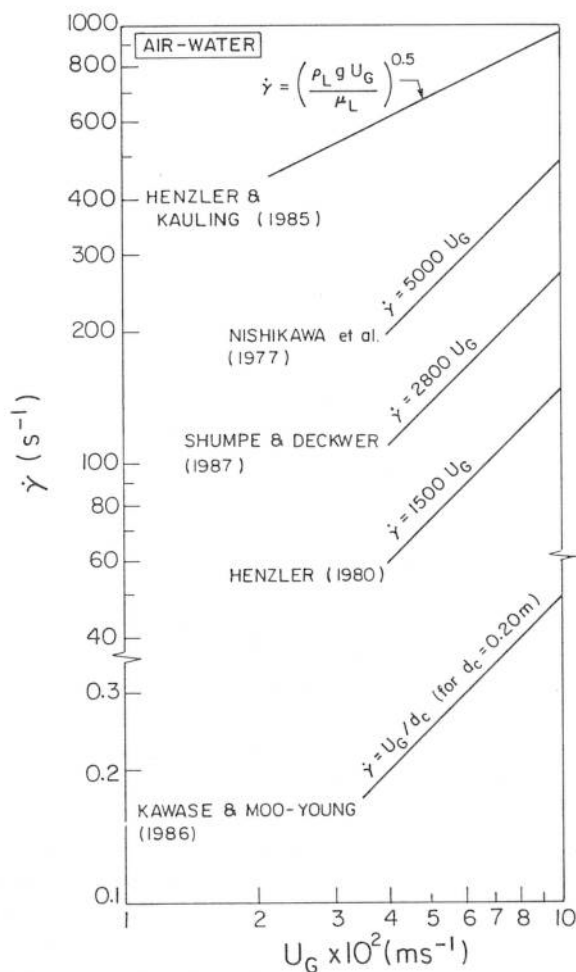


Figure 1. Average shear rate ($\dot{\gamma}$) in bubble columns (air-water) as a function of superficial gas velocity. The disparity among the various correlations is substantial.

there is a lack of agreement on the magnitude of shear rates in bubble columns under given operating conditions.

The foregoing observations draw attention to the observed discrepancies among interfacial area data reported by Popovic and Robinson⁴ and others.^{2,8} For correlation of such parameters as liquid circulation and the overall gas-liquid interfacial area, consideration of average shear rate in the reactor may be more appropriate because these parameters are dependent on conditions in the riser and the downcomer. Clearly, recent publications^{4,5} have not paid sufficient attention to this matter. Additional concerns related to the shear conditions in pneumatic bioreactors have been examined by us in a recent paper.⁹ Research which shows how phenomena such as induced liquid circulation in airlift bioreactors may be calculated without resorting to equation (2) has also been published.¹⁰

NOMENCLATURE

A_d	downcomer cross-sectional area (m^2)
A_r	riser cross-sectional area (m^2)
d_c	bubble column diameter (m)
g	gravitational acceleration ($m\ s^{-2}$)
K	consistency index ($Pa \cdot s^n$)
n	flow behavior index
P_G	power input due to gas (W)
U_G	superficial gas velocity (bubble column) ($m\ s^{-1}$)
U_{GR}	U_G based on airlift riser ($m\ s^{-1}$)
V_L	liquid volume in reactor (m^3)

Greek symbols

$\dot{\gamma}$	shear rate (s^{-1})
η_{eff}	effective liquid viscosity ($Pa \cdot s$)
μ_L	liquid viscosity (Newtonian) ($Pa \cdot s$)
ρ_L	liquid density ($kg\ m^{-3}$)

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