Determination of Effective Shear Rate in a Pilot-plant External Loop Airlift Reactor

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Abstract. Shear rate is an important design parameter in bio-reactors for its role in estimating cell-damage rate in shear-sensitive environment as well as in correlating hydrodynamics and mass transfer coefficients in non-Newtonian systems. One of the serious shortcomings in the analysis of non-Newtonian behaviour in airlift loop reactors is the lack of a reliable method for determining effective shear rate and viscosity appropriate to the airlift geometry.

This work has been carried out in a pilot-plant external loop airlift reactor of 6.5 m in height and 0.225 m diameter of both riser and downcomer. Biological media were simulated using non-Newtonian solutions of xanthan gum and carboxymethyl cellulose. The resulting shear rates are compared to the available literature, and show an increase in shear rate with increasing superficial gas velocity. Also, it has been found that non-Newtonian solutions with similar rheological properties and different chemical structure have different shear rate trends at a given superficial gas velocity.

Nomenclature

A_d	downcomer cross-sectional area, m^2
A_r	riser cross-sectional area, m^2
B	constant in Equation 3
g	acceleration due to gravity, $m.s^{-2}$

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h	heat transfer coefficient, $kJ.m.^{-2}.s^{-1}.^{o}C$
H	height, m
k	consistency index, $Pa.s^{n}$
n	flow behaviour index
V_{ld}	downcomer liquid circulation velocity, $m.s^{-1}$
V_{sg}	superficial gas velocity in the riser, $m.s^{-1}$

Greek letters

ε	gas hold-up
γ	shear rate, s^{-1}
μ	viscosity, Pa.s
ρ	density, $kg.m^{-3}$

Subscripts

av	average
b	bubble
d	downcomer
eff	effective
g	gas
l	liquid
r	riser
sg	superficial gas
ld	liquid downcomer
sl	superficial liquid

Abbreviations

ALR	airlift reactor
CMC	carboxymethyl cellulose
PVC	polyvinyl chloride
HV	high viscosity
MFM	magnetic flowmeter

Introduction

Airlift loop reactors are replacing conventional reactors for use as aerobic fermenters, because of their simple construction, low power input, good mass and heat transfer characteristics, and better defined flow patterns [1]. Shear rate is one of the indispensable parameters used in the design of aerobic fermenters for viscous non-Newtonian systems. Shear rate in airlift reactors has been investigated on a limited scale using correlations designed for bubble columns. Shear fields resulting from the fluid physical properties and the hydrodynamics may cause physical damage to fragile micro-organisms [2].

Effective viscosity (μ_{eff}) is one of the design parameters widely used in the literature to correlate mass transfer and hydrodynamic parameters for viscous non-Newtonian systems. There are many discrepancies in the literature concerning the effective viscosity of a non-Newtonian fluid. The Ostwald de Waele relation (or commonly known Power Law) is often used to describe the fluid's dependence on the shear rate:

$$\tau_L = k\gamma^n \tag{1}$$

Equation (1) can be written in the following form:

$$\mu_{eff} = k\gamma^{n-1} \tag{2}$$

In a given bioreactor, shear rate (γ) is a function of position, and actual measurement of local shear rate is complex [3-5]. There are many methods in the literature for estimating shear rate of non-Newtonian systems. The most reliable method of analysis is the analogical analysis which was first suggested by Metzner and Otto [6]. It is based on operating two identical stirred tank reactors, one containing Newtonian fluid and the other non-Newtonian fluid, under the same conditions, i.e. temperature, superficial gas velocity, impeller speed, etc. If these fluids are agitated in the laminar region, with the same impeller speed used in each, and one varies the viscosity of the Newtonian (by diluting or thickening) so that power measured at each impeller is the same, then, since all other variables are the same in both systems, one may say that the average viscosities are the same for both reactors. Nishikawa *et al.* [7] used the heat transfer coefficient from an immersed cooling coil and a jacketed wall in a bubble column as the measurable parameter. For the Newtonian system heat transfer coefficient (h) curves which are functions of the superficial gas velocity (V_{sg}) and the viscosity (μ) were constructed for all solutions. Similarly, for the non-Newtonian system h versus V_{sg} was developed for each solution. By keeping h and V_{sg} constant in the Newtonian and non-Newtonian system the effective viscosity was taken to be equal in both systems. The effective shear rate was calculated as a function of superficial gas velocity by:

$$\gamma_{eff} = BV_{sg} \tag{3}$$

The constant "B" was calculated to be 5000 m^{-1}. The above equation is valid for the range $0.04 \le V_{sg} \le 0.1$. The Nishikawa correlation (Eq. 3) has been used exclusively in the literature for bubble columns with gas-liquid and gas-liquid-solid viscous systems. It is important to note that heat transfer in bubble column reactors is controlled by the thin boundary layer on the reactor wall or coil, while mass transfer between bubble and liquid is controlled by the resistance in the liquid film around a bubble, thereby making the above correlation unsuitable for mass transfer studies [8]. In another study by Henzler [9] and Schumpe and Deckwer [10] the constant B was found to be 1500 and 2800 m^{-1}, respectively.

The only work directly related to the airlift loop configuration is that of Shi *et al.*

[11]. Glycerol solutions were used as the Newtonian medium and carboxymethyl cellulose (CMC) and xanthan gum solutions as non-Newtonian medium. The authors proposed the following quadratic equation for effective shear rate:

$$\gamma_{eff} = 14800V_{sg}^2 - 351V_{sg} + 3.26 \quad (4)$$

Equation (4) was found for a small airlift loop reactor, with an active volume of 0.04 m^3, with $A_d/A_r = 0.11$. The maximum working superficial gas velocity was limited to 0.06 m/s. A summary of the available correlations in the literature is presented in Table 1.

Experimental

A 0.7 m^3 external loop pilot-plant airlift reactor was used for this experimental study. The main components of the reactor were QVF borosilicate glass sections with the test sections fabricated from PVC. The experimental set-up is illustrated in Fig. 1 with a summary of the reactor dimensions given in Table 2.

Compressed air was filtered and controlled by a turbine flow meter (GH Flow Automation, UK), then sparged using a circular perforated plate with holes of 1mm diameter on a 11 mm pitch. The gas hold-up in the riser was measured using a differential pressure cell (Hitachi Co., Japan) with pressure tappings 3.32 m apart. Gas hold-up in the downcomer was estimated from an inverted U-tube manometer (filled with water) connected to tappings 1.1 m apart. The liquid velocity in the downcomer was measured

Table 1. Summary of effective shear rate correlations

Reactor	Authors	Correlation
Bubble column	Nishikawa et al. [7]	$\gamma_{eff} = 5000V_{sg}$
	Henzler [9]	$\gamma_{eff} = 1500V_{sg}$
	Schumpe and Deckwer [10]	$\gamma_{eff} = 2800V_{sg}$
Stirred tank and bubble column	Henzler and Kauling [15]	$\gamma_{eff} = \left(\left(\frac{P}{V} + V_{sg}\rho_l g\right)/\mu_{eff}\right)^{0.5}$
Airlift reactor	Shi et al. [11]	$\gamma_{eff} = 14800V^2_{sg} - 351V_{sg} + 3.26$

Table 2. Summary of reactor dimensions

Item	Dimension (m)
Riser diameter	0.225 (m)
Downcomer diameter	0.225 (m)
Downcomer to riser cross-sectional area, Ad/Ar	1.0
Dispersion height	6.5 (m)
Nominal riser length	7.5 (m)
Nominal downcomer length	9.6 (m)

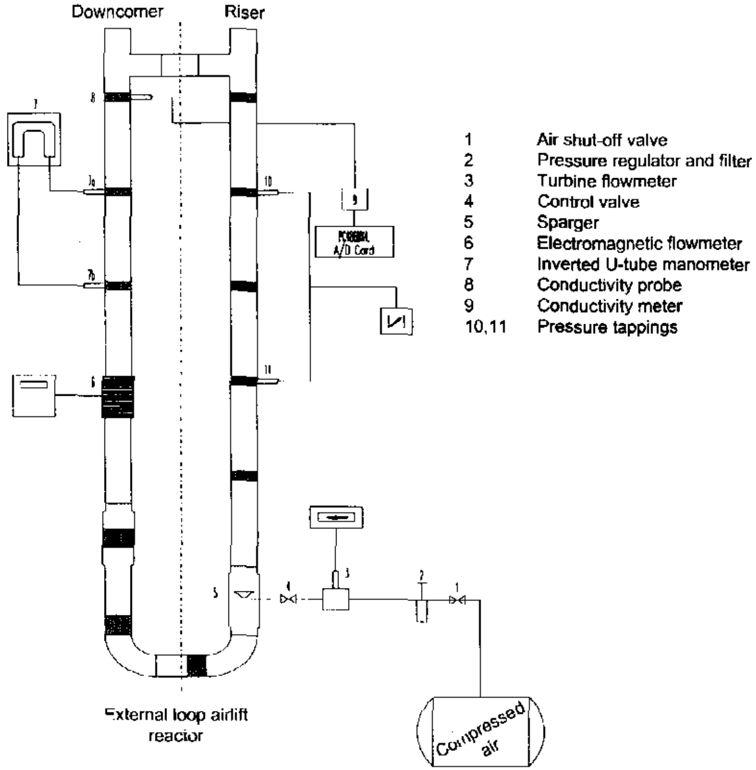

Fig. 1. Schematic of the experimental set-up.

using an electromagnetic flowmeter (Flowmetrix, RSA). The electromagnetic flowmeter measured the liquid velocity through the available area [12-13], hence the liquid circulation velocity is given by:

$$V_{ld} = (V_{ld})_{MFM}(1 - \varepsilon_d) \tag{5}$$

Non-Newtonian solutions used in this reactor, were sodium salt of carboxymethyl cellulose (Sigma Chemical Co., C8758, C4888, C5013) and xanthan gum (Sigma Chemical Co., practical grade, G1253). Glycerol (technical grade) solutions were used as the Newtonian medium. Normal tap water was used to make up the experimental solutions. The rheological properties of the solutions were examined using a Brookfield (USA) digital cylindrical spindle viscometer (Model LVDVII+). A Brookfield small sample adapter was used for the high viscosity solutions and the Brookfield ultra low adapter was used for low viscosity solutions. The rheological properties of the non-Newtonian solutions used in this work are presented in Table 3.

Results and Discussion

If two systems are operating under the same conditions, e.g. superficial gas velocity, temperature, pressure, and if one measurable characteristic parameter is identical, it can be said that the effective viscosity in both systems is equal. In this work, the liquid circulation velocity was chosen as the measurable parameter because of its relationship to the shear rate. Shear rate is a function of the relative velocity between the bubble and the liquid, and between the liquid and the reactor wall. Liquid circulation is induced by the difference in gas hold-up between the riser and the downcomer, which in turn is determined by the superficial gas velocity. When the velocity of the bubble is increased, the residence time within the reactor is reduced, leading to a lower gas hold-up, hence the relationship between V_{gl} and the speed of the rising bubble. The wall and the change in direction of fluid as it goes around the loop are the main resistances to liquid circulation, therefore the relationship between shear rate and liquid circulation velocity appears logical.

Table 3. Rheological properties of non-Newtonian solutions

Solution	wt%	n	k
Xanthan 1	0.15	0.3956	0.2696
Xanthan 2	0.20	0.3206	0.5187
Xanthan 3	0.25	0.2922	0.8365
Xanthan 4	0.30	0.2649	1.2039
Xanthan 5	0.35	0.2355	1.6664
CMC 1	0.30	0.9296	0.1472
CMC 2	0.35	0.8077	0.1742
CMC 3	0.40	0.7990	0.2629

The effective viscosity of the xanthan gum and CMC is based on the analogical comparison with solutions of glycerol. For each solution of glycerol, V_{ld} and V_{sg} data was plotted and by keeping the viscosity constant, points for the V_{sg} curves in Fig. 2 were derived. For the xanthan gum and glycerol solutions there was foaming at the high gas flow rates, which led to fluid loss through the overflow, and a reduction in the liquid circulation velocity. The upper range of the superficial gas velocity used was thus limited by system foaming.

Since the work of Shi *et al.* [11] is the only one applicable to the external loop configuration, this experimental work was confined to the range of flow behaviour index (n = 0.404-0.937) and the fluid consistency index (k = 0.0783-0.33) used by them, for the purpose of comparison and scale-up. While experiments were carried out with solutions having n and k falling in the above ranges, most of the data could not be used, as the liquid circulation velocity was too high, and did not fall in the range of the glycerol curve constructed in Fig. 2. This could be attributed to the difference in reactor geometry between this work (A_d/A_r = 1) and Shi *et al.* [11] (A_d/A_r = 0.11). Popovic and Robinson [14] reported (an increase in V_{sl} by a factor of 3, as A_d/A_r was increased from 0.111 to 0.444 for the same operating conditions and rheological behaviour as in this work. The range of n and k therefore had to be extended to accommodate the V_{sl} range of the reactor and the range for glycerol viscosity shown in Fig. 2. For each solution of CMC and xanthan gum,

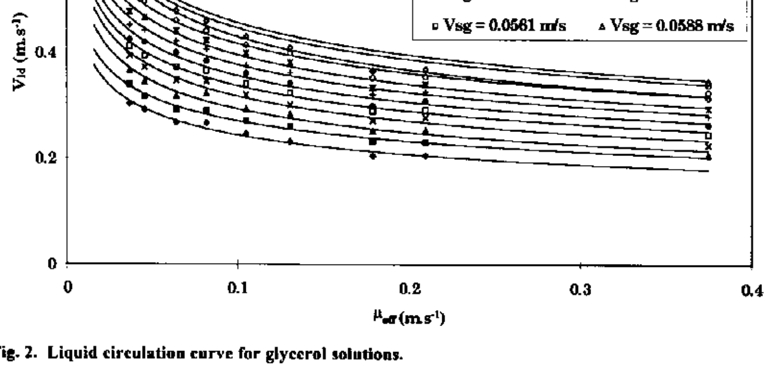

Fig. 2. Liquid circulation curve for glycerol solutions.

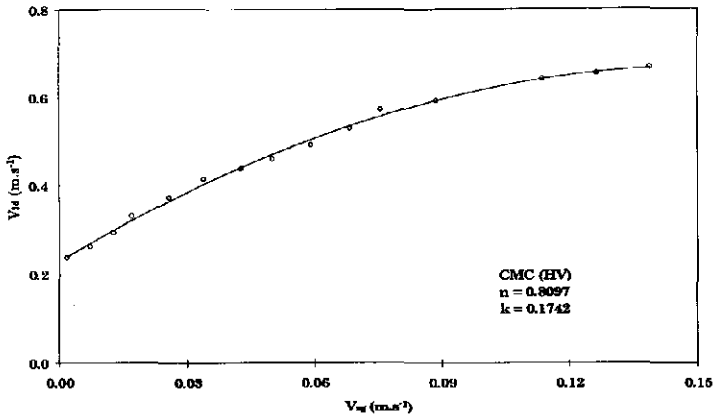

Fig.3. Sample plot of liquid circulation velocity in the downcomer versus superficial gas velocity.

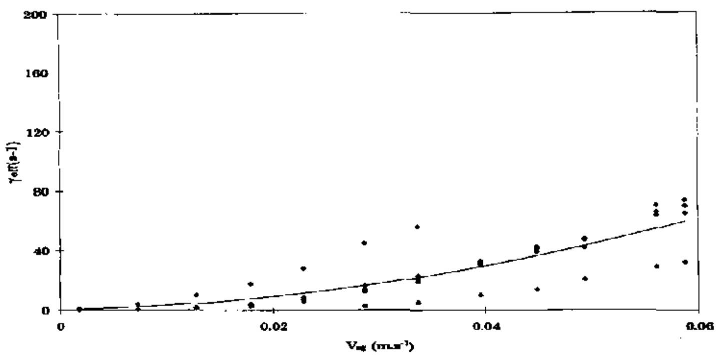

Fig. 4. Effective shear rate for xanthan gum solutions.

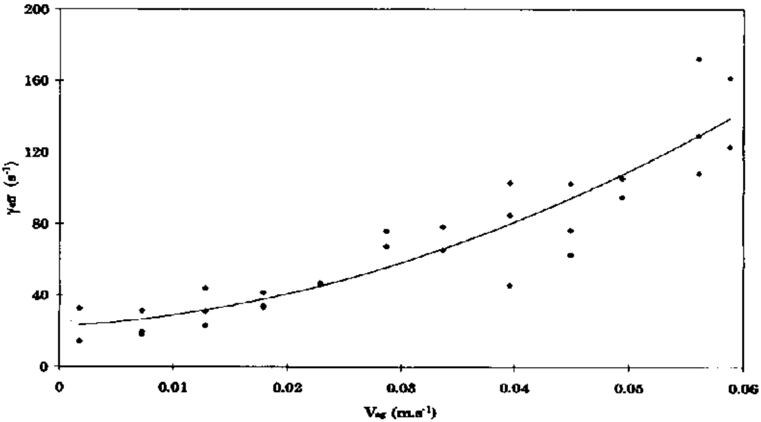

Fig. 5. Effective shear rate for carboxymethyl cellulose solutions (high viscosity).

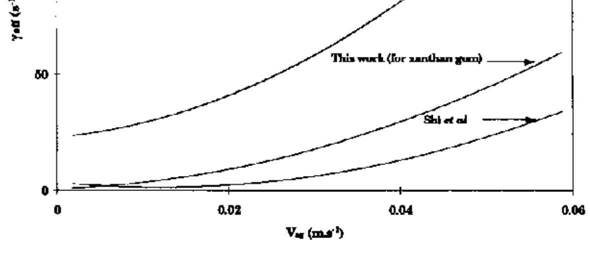

Fig. 6. Comparison of effective shear rate with Shi *et al.* [11], for xanthan gum and CMC.

a curve of V_{ld} versus V_{sg} (Fig, 3) was constructed for analogy with the glycerol system in Fig. 2. By keeping V_{ld} and V_{sg} constant for the non-Newtonian system and for the glycerol system, the effective viscosity was taken to be equal for both systems. Using Equation 3 the effective shear rate was calculated using the experimental values of k and n, and in this way the shear rate was correlated for each V_{sg} data point.

It has been found, in contrary to Shi *et al.* [11], that non-Newtonian solutions with similar rheological properties and different chemical structure will have different shear rate at a given superficial gas velocity. Therefore, the effective shear rate for xanthan gum and CMC was plotted separately as a function of V_{sg} in Fig. 4 and Fig. 5, respectively.

The results of this work are compared to those of Shi *et al.* [11] in Fig. 6. The effective shear rate for this work is higher than that predicted by Shi *et al.* correlation for a given V_{sg}, for both xanthan gum and CMC solutions. As mentioned above the effect of term (A_d/A_r) reported by Popovic and Robinson [14] can be used to explain the higher shear rate for this reactor geometry. As A_d/A_r increases, V_{ld} increases for the same V_{sg}, hence the effective viscosity determined from the glycerol curve (Fig. 2) is lower for this work. From Equation 2, if m_{eff} is decreased for the same k and n, the shear rate increases, thereby explaining the higher shear rate in this work.

Experimental data of this work are compared to the predictions by the available correlations in the literature for bubble columns and external loop airlift reactors (Fig. 7). The most widely used correlation proposed by Nishikawa *et al.* [7] shows the effective shear rate to be higher than the work of Henzler [9] and Schumpe and Deckwer [10]. Although the results of calculations of effective shear rate in bubble columns are different from each other, it was found that the effective shear rate is lower in external loop airlift reactors, except for the work of Henzler [9] which falls below the CMC curve for this work. Henzler obtained a value of B (Eq. 3) to be an adjustable parameter to be fitted by regression analysis of the mass transfer data.

For bubble columns, circulation comprises an upward flow with the liquid relatively rich in entrained bubbles and compensating downward flow with liquid poor in bubbles. This countercurrent flow increases the relative velocity between the liquid and the bubbles; and hence increases the effective shear rate. For airlift reactors, the concurrent flow of gas and liquid, both in the riser and the downcomer, reduces the relative velocity between the bubbles and the liquid. This leads to lower effective shear rates in airlift reactors than for bubble columns. Therefore external loop airlift reactors are more appropriate than bubble columns for the cultivation of plant and animal cells which are sensitive to high shear rates.

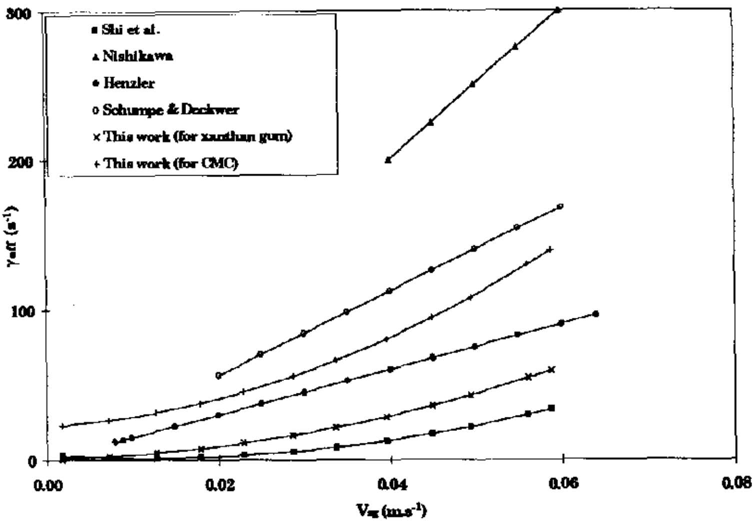

Fig.7. Effective shear rate comparison for bubble columns and external loop airlift reactors.

Conclusions

Airlift reactors are promising for their potential application to the growth of animal and plant cells. Shear rate was determined for viscous non-Newtonian solutions by analogy with Newtonian solutions using liquid circulation velocity as the characteristic parameter between the two systems.

It has been found that shear rate increases with increasing superficial gas velocity, and by comparison with literature, increases with increasing the A_d/A_r ratio. In this work it has been confirmed that non-Newtonian solutions with similar rheological properties and different chemical structure will have different shear rate profiles.

By comparison with data presented in the literature, airlift reactors, show low shear rate values than those found in bubble column reactors.

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دراسة معملية لمعدل القص التقديري في مفاعل دفع هوائي صناعي حلقي

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ملخص البحث. يعتبر إيجاد معدل القص في المفاعلات العمودية الحلقية ذات الدفع الهوائي من الخطوات المهمة لتحديد معدل الضرر للخلايا الحية الحساسة للقص في الأوساط الحيوية ذات السلوك اللانيوتوني ، وكذلك معرفة علاقة ترابط معاملات قوى الموائع وانتقال المادة. إن عدم وجود طريقة يعتمد عليها في إيجاد معدل القص ومعامل اللزوجة التقديريين والمناسبين في المفاعلات الحلقية أدى إلى وجود عيوب كثيرة في تحليل السلوك اللانيوتوني في المفاعلات الحلقية ذات الدفع الهوائي.

لطرح مزيد من الضوء على معدل القص في المفاعلات الحلقية ذات الدفع الهوائي ، تمت في هذه الدراسة تجارب معملية في مفاعل حلقي صناعي مصنوع من الزجاج البروسيلي ، بارتفاع قدره ٦,٥م ونصف قطر قدره ٠,٢٢٥م لكل من الطرف الصاعد والهابط على السواء. ولمحاكاة الحالة اللانيوتينية المشتهرة في الأوساط الحيوية تم استخدام محاليل صمغ الزانثان و كاربوكسيلات الميثيل السليلوزية لتقارب خواصهما الطبيعية مع الأوساط الحيوية.

بعد مقارنة معدلات القص المعملية في هذه الدراسة وما هو موجود بالمراجع ، اتضح أن معدل القص يزيد بزيادة كل من السرعة السطحية للغاز الداخل ونسبة مساحة مقطع الهابط والصاعد. كذلك وجدت علاقة بين الخصائص الفيزيائية للمحاليل اللانيوتونية ومعدل القص في حالة تقارب خصائصها الريولوجية.