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NOTE

Estimation of a characteristic friction velocity in stirred benthic chambers

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ABSTRACT: The ecology of water bodies can be greatly affected by the flux of solutes across the sediment–water interface. This solute flux is frequently measured using either benthic chambers in the field or incubated sediment cores, where in both cases the sediment is removed from the influence of the natural hydrodynamics. To compensate, the overlying water is usually stirred in some manner, e.g. with a rotating impeller, in an attempt to reproduce the natural field conditions. The hydrodynamics affect the diffusive-boundary-layer thickness, which can be one of the major controls on solute flux magnitude. Thus, a quantitative understanding of the effects of chamber stirring is vital. In this paper a characteristic friction velocity is presented as a function of a given stirrer configuration and stirring rate. The developed scaling relationship correlates well ($R^2 \approx 0.9$) with previously reported friction velocities in benthic chambers, over a range of chamber configurations and sizes. It is now possible, using this equation for characteristic friction velocities, to ensure that benthic chambers experience similar turbulence intensities to natural environments, without elaborate turbulence measurements.

KEY WORDS: Benthic chamber · Friction velocity · Porewater fluxes

INTRODUCTION

The rate of solute transport across the sediment–water interface is often important when determining a nutrient budget for a water body or investigating the fate of a contaminant (Jorgensen & Revsbech 1985, Maran et al. 1995). The solute transport across the interface is affected by biological and chemical processes within the sediments, as well as by the benthic hydrodynamics. *In situ* benthic chambers are frequently used to estimate these solute fluxes, where it is assumed that the presence of the chamber does not alter sediment processes, and stirrers are frequently installed within the chambers to simulate benthic hydrodynamics (see e.g. Crawford & Sanford 2001). While the interaction between turbulence and ecosystem function has been considered in some detail in surface waters (Sanford 1997), particularly with respect to phytoplankton productivity, there is much less understanding of the effect of near-bottom mixing processes on benthic–pelagic coupling. Therefore, we have limited confidence that benthic chambers are able to simulate those characteristics of benthic hydrodynamics that are pivotal for controlling benthic fluxes.

The sediment biology and chemistry are well documented, both inside and outside benthic chambers (see e.g. Boudreau & Jørgensen 2001). In comparison, interfacial hydrodynamics is poorly understood, in part because of the extreme difficulty in measuring the hydrodynamics close to the sediment–water interface, without contamination of the signal. As a result, simplified conceptual models of the interfacial hydrodynamics are necessary, and to date they have proved very useful for parameterisation of solute fluxes. These models are based on the concept of a viscous boundary layer (VBL), typically around 1 cm thick, in which viscous forces start to damp turbulent eddies. It is usually assumed that, closer to the sediment, there is a diffusive boundary layer

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(DBL), in which turbulence is suppressed to such an extent that molecular diffusion is the dominant means of solute transport. These concepts were originally developed and validated for open-channel flow, where unidirectional flows are adjacent to solid walls. When flows are adjacent to a permeable medium such as sediments, where the no-slip condition at the boundary may be relaxed, these concepts become ambiguous, particularly under the turbulent conditions experienced in nearly all benthic environments. Recently, the persistence and nature of the DBL under turbulent conditions has been questioned (Guss 1998). However, these concepts continue to be used in the study of benthic processes, and DBLs have been measured in the field and in laboratory experiments by a number of research groups.

DIFFUSIVE BOUNDARY LAYER THICKNESS

If we do assume that a DBL exists adjacent to permeable sediments, then the thickness of the DBL becomes a major control on solute fluxes and depends on the level of turbulence in the overlying water and the molecular diffusion coefficient of the solute. Typical DBL thicknesses for dissolved oxygen range from about 0.1 to 1.5 mm (Santschi et al. 1983, Archer et al. 1989).

The resistance to solute transport caused by the DBL may be modelled as a 'stagnant film' of a certain thickness, across which only molecular diffusion operates. This will result in a solute concentration profile that has a linear gradient within the DBL but is constant in the well-mixed water column. This model is an approximation of the real concentration profile, where the transition between the turbulent bulk of the fluid and the DBL is more gradual (Santschi et al. 1983). In the stagnant film model, Fick's First Law becomes:

$$J = -D\frac{[S]_2 - [S]_1}{\delta z} \quad (1)$$

where J is the areal mass flux (kg m^{-2} s^{-1}), D is the molecular diffusion coefficient of the solute (m^2 s^{-1}), δz is the thickness of the stagnant film (m), $[S]_2$ is the solute concentration at the sediment surface (mg l^{-1}) and $[S]_1$ is the solute concentration in the overlying water (mg l^{-1}). Eq. (1) can alternatively be written as:

$$J = -K([S]_2 - [S]_1) \quad (2)$$

where K is a mass-transfer velocity (m s^{-1}), defined as the ratio of the molecular diffusion coefficient to the film thickness.

Some models estimate DBL thickness from experimental data and thus predict solute fluxes using Eq. (1) (e.g. Glud et al. 1995, Hondzo 1998). Probstein (1989) estimated δz for the case of mean horizontal flow over the sediment–water interface as:

$$\delta z = C_1\left(\frac{\nu}{u_*}\right)Sc^{-1/3} \quad (3)$$

where ν is the kinematic viscosity (m^2 s^{-1}), Sc is the dimensionless Schmidt number (ratio of ν to D) and u_* is the friction velocity (m s^{-1}). Rahm & Svensson (1989) estimated the constant of proportionality, $C_1 = 5$, based on the assumed thickness of a viscous sublayer, and Dade (1993) suggested $C_1 = 10$. Steinberger & Hondzo (1999) conducted experiments under unidirectional flow, measured the DBL thickness with an oxygen microprobe, and experimentally determined $C_1 = 19.4$.

An alternative model for predicting DBL thickness has been proposed by Bilger & Atkinson (1992), based on the mean flow velocity and the Stanton number, which is the ratio of the rate of transfer (of mass or heat) between a fluid and a surface to the rate of advection of fluid past the surface. The Stanton number can be written as a mass transfer coefficient or equivalent stagnant film thickness, resulting in an equation of the same form as Eq. (3). The constant of proportionality will depend on the model used (see e.g. Bejan 1995 for more detail).

In summary, different models give a similar form for the dependence of the DBL thickness on flow and fluid properties; however, debate remains regarding C_1 in expressions such as Eq. (3).

FRICTION VELOCITY CREATED BY ROTATING STIRRERS

It is important to characterise the hydrodynamics imposed by the mechanical stirring in either mesocosm or benthic chamber studies in order to investigate the impact on the measured solute fluxes across the sediment–water interface, and thus the validity of Eq. (3) and the value of C_1. A key parameter used to quantify the hydrodynamics experienced at the sediment–water interface is the friction velocity, u_*, which appears in Eq. (3). Estimation of u_* is dependent on the hydrodynamic-forcing method. Three different methods have been used to impose specific hydrodynamic conditions in laboratory tanks, mesocosms and benthic chambers. An oscillating grid may be used to simulate zero mean flow, nearly homogeneous turbulence, as might be experienced by sediments in shallow lakes during periods of night-time convective cooling, for example. While oscillating grids have been used to simulate water-column mixing (e.g. Turner 1973), they have only recently been used successfully to investigate the effects of turbulence on sediment resuspension (Orlins & Gulliver 2003). Flumes have been used to force uni-directional flow over sediments (e.g. Huettel et al. 1996), and more recently the racetrack design has been used to minimise chemical losses from the flume system and thus allow easier measurement of solute fluxes (Cornelisen & Thomas 2002).

Estimation of u_* both for oscillating grids and in particular flumes (both rectangular and racetrack designs) is relatively simple; it relies on an established hydrodynamic understanding of these more complex experimental set-ups. However, much more common than either the oscillating grid or the flume is the use of paddles or stirrers to create flow over sediments within mesocosms or benthic chambers. While the hydrodynamic and turbulent characteristics of such stirred chambers have been detailed in the chemical-engineering literature, most users of these very simple systems rarely access this literature. The result is a large number of published measurements of sediment–water solute fluxes with minimal, or often no, statement of the hydrodynamic conditions under which the measurements were made. In this paper we develop a simple method to estimate the characteristic friction velocity created by a range of stirrer types using scaling arguments. This

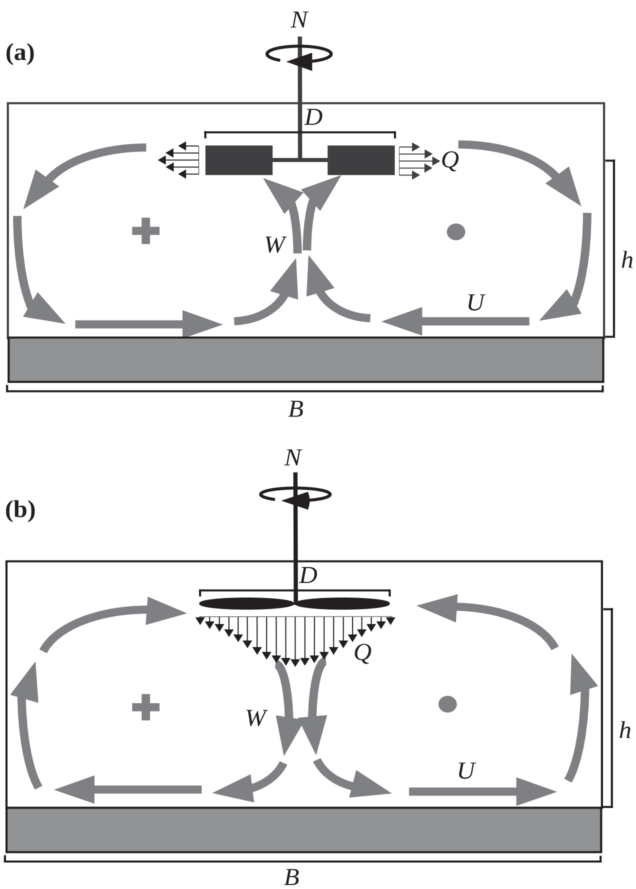

Fig. 1. Hydrodynamics within benthic chambers, showing the flow created by (a) radial-flow impellers and (b) axial-flow impellers

simple method should allow non-hydrodynamicists to design and operate stirred benthic chambers such that the hydrodynamic conditions within the chamber are similar to those found in the natural environment.

There are 2 fundamentally different types of stirrers used in wastewater treatment, biological reactors, process engineering and benthic chambers. Radial-flow impellers rely on centrifugal forces to drive fluid out from the ends of the impeller tips, creating a large-scale circulation as shown in Fig. 1a. Examples of radial-flow impellers are stirrer bars and disk stirrers. In contrast, axial-flow impellers use lift forces to drive flow along the axis of rotation (Fig. 1b). Any impeller with asymmetric blades, e.g. ceiling fans, creates axial flow. The discharge flow, Q ($m^3\ s^{-1}$), created by both radial and axial impellers can be modelled as:

$$Q \sim ND^3 \sim ND \cdot D^2 \tag{4}$$

where N is the impeller rate of rotation (s^{-1}) and D is the impeller diameter (m) (Oldshue 1983). While the total entrained flow rate established by the impeller is usually 2 to 2.5 times the impeller discharge flow rate (Nienow 1997), the scaling shown in Eq. (4) remains.

It is important to note that all impellers create a secondary vortical circulation which may dominate the return-flow circulation shown in Fig. 1a. This vortical circulation may impact on u_* at the sediment–water interface; it creates pressure fluctuations within the sediments which can drive porewater fluxes (Khalili et al. 1997); and it reduces vertical mixing within the chamber (Oldshue 1983). In stirred reactors, it is standard practice to install axial baffles which prevent this vortical circulation (Oldshue 1983); however, to our knowledge, such a configuration has not been implemented in benthic chambers.

For radial-flow impellers, conservation of mass requires that the discharge radial flow rate, Q, scales with the rate of upward flow drawn towards the impeller, Q_u. Then, the appropriate steady-state vertical-velocity scale, W, can simply be written as:

$$W \sim ND \tag{5}$$

and the horizontal area of the discharged stream scales as D^2. Eq. (5) also holds for axial-flow impellers, for which W is the velocity scale of fluid driven downwards from the impeller blades.

For the whole of a circular benthic chamber, we can use the conservation of mass in cylindrical coordinates:

$$\frac{1}{r}\frac{\partial}{\partial r}(ru_r) + \frac{\partial w}{\partial z} = 0 \tag{6}$$

where we have assumed that the swirl or azimuthal velocity component, u_θ, is independent of θ. Rather than solve this equation exactly, we are interested in order-of-magnitude estimates. Thus, we take $u_r \sim U$, $w \sim W$, $z \sim h$ and $r \sim B$, where U is the steady-state horizontal velocity scale in the chamber (cm s^{-1}), h is the height from the sediments to the stirrer (cm), and B is the width or diameter for the chamber (cm). Eq. (6) then implies a relationship between the horizontal and vertical velocities:

$$\frac{U}{B} \sim \frac{W}{h} \qquad (7)$$

Substituting Eq. (5) and rearranging gives:

$$U \sim W\frac{B}{h} \sim ND\frac{B}{h} \qquad (8)$$

In open-channel flow it has been shown that the friction velocity, u_*, is proportional to the mean velocity in the channel. Therefore, we assume that in benthic chambers the friction velocity is also proportional to the characteristic mean velocity scale in the radial direction, given in Eq. (8), via an unknown coefficient:

$$u_* = C_2 U = C_3 ND\frac{B}{h} \qquad (9)$$

EXPERIMENTAL VALIDATION

To test our scaling, we use data from 2 studies where u_* has been measured directly by hot film sensors at the sediment–water interface (Buchholtz-ten Brink et al. 1989, Huettel & Gust 1992). The majority of stirrers used in the studies were radial-flow impellers (rotating bars, rods and disks); however, a few measurements were made using paddles, which are axial-flow impellers. Our estimated velocities are well correlated to the measured friction velocities (Fig. 2). For axial flow impellers,

$$u_* = 0.05ND\left(\frac{B}{h}\right) \qquad R^2 = 0.93 \qquad (10)$$

and for radial flow impellers,

$$u_* = 0.023ND\left(\frac{B}{h}\right) \qquad R^2 = 0.88 \qquad (11)$$

Note that, while the scaling is identical for both axial- and radial-flow impellers, the value of the coefficient C_3 in Eq. (9) is not necessarily the same, as shown in Eqs. (10) & (11). Both type of impeller will create vortical secondary flows (given that none of these benthic chambers contained baffles), but the intensity of that circulation will vary with impeller type. It is expected that the vortical circulation will modify the friction velocities felt at the sediment–water interface.

The friction velocity in a fully turbulent chamber is equivalent to the root-mean-square (rms) turbulent velocity (Oldham & Lavery 1999), and Eq. (10) is very similar to a relationship previously reported by Jaworski et al. (1991) and Vrábel et al. (2000) for axial-flow impellers:

$$u'_{\mathrm{rms}} = 0.05\pi ND \qquad (12)$$

In the chamber data used to validate Eq. (10) (shown in Fig. 2), B/h ranges from 3 to 3.75, very close to the value of π, and thus it would be of interest to test the result in Eq. (10) over a wide parameter range of B/h.

A key assumption in both the above scaling arguments and the parameterisation of the DBL thickness is that the external flow is steady and the boundary layer fully developed. To achieve this, stirring must be maintained at constant operating conditions. Therefore, these results cannot be compared to continually oscillating forcing conditions, as studied by Crawford & Sanford (2001) for example. For that study, paddles within the mesocosms were rotated 7.5 times in one direction, stopped for 15 s, then rotated 7.5 times in the opposite direction, and the authors measured effective values of u_* in this unsteady forcing environment.

CONCLUSIONS

In summary we have presented a simple method for estimating the characteristic friction velocity of stirred benthic chambers. This allows researchers, across a

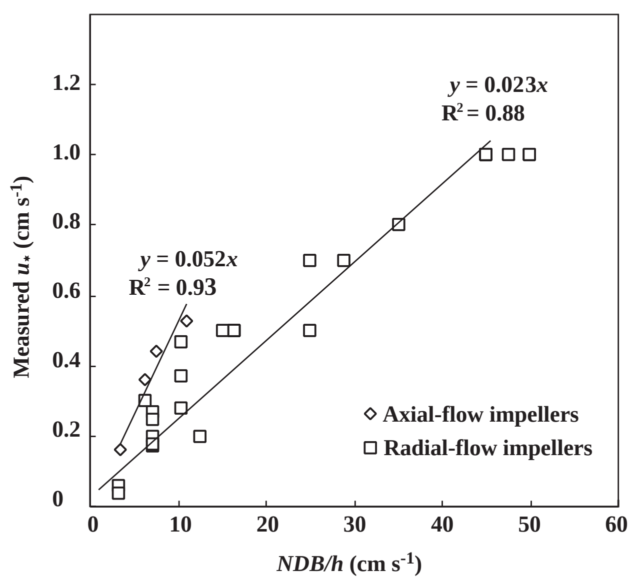

Fig. 2. Comparison of the measured friction velocity with the characteristic friction velocity as predicted by Eq. (9). Data from Buchholtz-ten Brink et al. (1989) for 3 different stirring devices and Huettel & Gust (1992) for 2 different chamber shapes and stirring devices

range of scientific disciplines, to ensure that hydrodynamic conditions inside chambers or vessels are similar to those experienced in the field. The relationships stated in Eqs. (10) & (11) also allow researchers to test the validity of Eq. (3) without elaborate measurement of turbulence characteristics.

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