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Contaminant transport from point source on water surface in open channel flow with bed absorption

Jinlan Guo, Xudong Wu, Weiquan Jiang*, Guoqian Chen*

College of Engineering, Peking University, Beijing 100871, China

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ABSTRACT

Studying solute dispersion in channel flows is of significance for environmental and industrial applications. Two-dimensional concentration distribution for a most typical case of a point source release on the free water surface in a channel flow with bed absorption is presented by means of Chatwin's long-time asymptotic technique. Five basic characteristics of Taylor dispersion and vertical mean concentration distribution with skewness and kurtosis modifications are also analyzed. The results reveal that bed absorption affects both the longitudinal and vertical concentration distributions and causes the contaminant cloud to concentrate in the upper layer. Additionally, the cross-sectional concentration distribution shows an asymptotic Gaussian distribution at large time which is unaffected by the bed absorption. The vertical concentration distribution is found to be nonuniform even at large time. The obtained results are essential for practical implements with strict environmental standards.

1. Introduction

Studying solute dispersion in channel flows is of great significance for environmental and industrial applications, such as environmental risk assessment, wastewater treatment engineering and ecological restoration (Fischer, 1976, 1973; Guerrero et al., 2010; Wu et al., 2011; Wu and Chen, 2012). To comprehend the transport process of solute in flows, Taylor dispersion emerges as a fundamental concept, which refers to the process that injected solute spreads under the combined effects of velocity non-uniformity and diffusion. The long-term evolution of transverse mean concentration distribution can be described by a diffusion-like model, corresponding to a Gaussian distribution (Taylor, 1953, 1954). The effective diffusivity has been verified by Aris's moments analysis (Aris, 1956) and Chatwin's long-time asymptotic technique (Chatwin, 1970). This classic model has attracted extensive attention and found wide applications (Davidson and Schroter, 1983; Grotberg et al., 1990; Sarkar and Jayaraman, 2002; Shankar and Lenhoff, 1991; Yasuda, 1984). Particularly, numerous studies on solute dispersion in open channel flows (Wang and Chen, 2016a; Li et al., 2017; Ng, 2000; Ng and Yip, 2001), wetland flows (Wang and Huai, 2018; Luo et al., 2017; Jiang et al., 2017; Luo et al., 2016; Chen, 2013), tube flows (Wang et al., 2015; Ng, 2002; Wu and Chen, 2012) or natural rivers (Wang et al., 2017; Wang and Huai, 2016), etc. have been conducted.

Among these applications, many studies focused on the model of Taylor dispersion with bed absorption (Berkowitz and Zhou, 1996; Berkowitz, 2002; Wang and Chen, 2016b), which can characterize the ecological effects of the natural water bodies in degrading pollutants (Dagan, 1987; Zeng et al., 2010; Berkowitz, 2002; Wu et al., 2011). For example, Smith (1983),Smith (1986) studied the effect of boundary absorption upon longitudinal dispersion in shear flows. Mazumder and Das (1992) revealed that the dispersion coefficient decreases with the absorption parameter, and the increased wall absorption causes negatively skewed deviations from Gaussianity. Mondal and Mazumder (2005) presented the longitudinal dispersion of passive tracer molecules released in an incompressible viscous fluid flowing through a channel with reactive walls under the active walls. Moreover, Ng (2006) determined the Taylor dispersion coefficients in the one-dimensional effective diffusion equation for solute dispersion in an open channel flow with boundary reaction. Nevertheless, these studies exclusively focused on the asymptotic mean concentration distribution of the solute transport process, and assessment of the absorption effect was simply based on the longitudinal mean concentration (Berkowitz and Zhou, 1996).

Actually, the cross-sectional concentration distribution is far from uniform at the initial time and even for a long time (Wu et al., 2011; Wu and Chen, 2014a; Wang et al., 2013, 2015; Wang and Chen, 2016c). Moreover, the effect of bed absorption further reshapes the vertical concentration distribution to form larger nonuniformity (Sankarasubramanian and Gill, 1973; Wang and Chen, 2016b). In many

* Corresponding authors.
E-mail addresses: wqjiang@pku.edu.cn (W. Jiang), gqchen@pku.edu.cn (G. Chen).

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practical applications, such as environmental risk assessment (Zeng et al., 2014), most concerned indicator is the influenced region, where the concentration is beyond some given environmental standards. Apparently, the influenced region is sensitive to the detailed cross-sectional concentration distribution, rather than the cross-sectional mean. Therefore, there remains a need for vertical concentration distribution. Recent efforts have been undertaken to study the cross-sectional or vertical concentration distribution in various flows by different methods. To be specific, Wu and Chen (2014b) presented explicit solutions for the cross-sectional concentration distribution in a pipe flow by perturbation analysis, as verified and extended in Wang and Chen (2016c) in terms of the Aris-Gill expansion. Later, Wang and Chen (2017b) illustrated the two-dimensional concentration distribution in wetland flow with bulk degradation and bed absorption with the method of concentration moments. It is worth noting that Wang and Chen (2016b) studied the vertical concentration distribution for solute dispersion in an open channel flow with bed absorption by extending the Aris-Gill expansion (Aris, 1956; Gill, 1967; Gill and Sankarasubramanian, 1970). Their results verified that there exists a tremendous non-uniformity in the vertical concentration distribution.

However, these studies consistently adopted the initial condition of an uniform and instantaneous contaminant release over the cross-section of flows. For a point source release on the free water surface in a channel flow, which is a most practical case in environmental risk assessment as encountered in the leakage of toxic chemicals in waters (Fischer et al., 1979; Fu et al., 2016), the vertical concentration distribution will be more nonuniform which should be further investigated. Latini and Bernoff (2001) disclosed that there are three regimes for the classical problem of dispersion of a point discharge of tracer in laminar pipe Poiseuille flow and only at large times, the flow is in the classical Taylor regime, for which the tracer is homogenized transversely across the pipe and diffuses with a Gaussian distribution longitudinally. Therefore, the full time evolution of the concentration distribution of the contaminant transport process from a point source release in a channel flow needs to be studied, which is critical to environmental risk assessment (Wang and Chen, 2016a).

In this regard for point source release on the free water surface, recently Fu et al. (2016) have revealed an additional longitudinal displacement for contaminant dispersion in a wetland flow without bed absorption. Their work focused on the transverse mean concentration distribution at large time. In this study, efforts will be made to present general solutions by considering the skewness and kurtosis of the concentration distribution in the initial time and analyzing the effect of bed absorption on the dispersion process.

In this work, we theoretically study the contaminant transport from a point source release on the water surface in an open channel flow with bed absorption by means of Chatwin (1970)'s long-time asymptotic technique. The main contents of this work are: (I) to discuss the five basic characteristics of Taylor dispersion; (II) to analyze the full time evolution of the cross-sectional mean concentration distribution with higher order modifications by considering its skewness and kurtosis; (III) to present the complete two-dimensional concentration distribution of the contaminant transport process. The effect of bed absorption on the dispersion process is thoroughly discussed.

2. Method

2.1. Formulation for contaminant transport

For contaminant transport from a point source release on the free water surface in an open channel flow with bed absorption, the right-handed Cartesian coordinate system Ox^*z^* is set as shown in Fig. 1, where the water depth is h^*,x^*-axis is taken to be longitudinal, z^*-axis is taken to be vertical, and Origin O is set at the channel bed wall. The convection–diffusion equation is

$$\frac{\partial C^*}{\partial t^*} + u^*(z^*)\frac{\partial C^*}{\partial x^*} = D^*\left(\frac{\partial^2 C^*}{\partial x^{*2}} + \frac{\partial^2 C^*}{\partial z^{*2}}\right), \tag{1}$$

where $C^*(x^*,z^*,t^*)$ is the concentration, t^* is time, $u^*(z^*)$ is flow velocity, $D^*(z^*)$ is the solute diffusivity. For a steady laminar flow in the open channel, the transverse velocity profile can be depicted as

$$u^*(z^*) = u^*_{\max}\frac{z^*}{h^*}(2-\frac{z^*}{h^*}), \tag{2}$$

where $u^*_{\max}$ is the maximum velocity on the free water surface.

Consider a point source release on the water surface with mass Q^*, the initial condition can be set as

$$C^*(x^*,z^*,0) = Q^*\delta(x^*)\delta(h^*-z^*), \tag{3}$$

where $\delta(x^*)$ is the Dirac delta function.

The non-penetration condition at the free water surface is

$$\frac{\partial C^*(x^*,h^*,t^*)}{\partial z^*} = 0. \tag{4}$$

Consider the contaminant absorbed to the substrate is described by the linear first-order irreversible absorption (Ng and Yip, 2001; Berkowitz and Zhou, 1996; Dijk and Berkowitz, 1998; Purnama, 1988), the boundary condition at the channel bottom gives

$$D^*\frac{\partial C^*(x^*,0,t^*)}{\partial z^*} = \beta^* C^*(x^*,0,t^*), \tag{5}$$

where is the bed absorption parameter.

Since Q^* is finite, the upstream and downstream conditions are

$$C^*(\pm\infty,z^*,t^*) = 0. \tag{6}$$

We use the bracket to denote the mean of a quantity over cross-section, e.g.,

$$\langle u^*\rangle = \frac{1}{h^*}\int_0^{h^*} u^*\,\mathrm{d}z^*, \tag{7}$$

where $\langle u^*\rangle$ is the mean velocity.

Then introducing the following dimensionless parameters:

$$x = \frac{D^*(x^*-\langle u^*\rangle t^*)}{\langle u^*\rangle h^{*2}},\quad z = \frac{z^*}{h^*},\quad t = \frac{D^*}{h^{*2}}t^*,\quad u = \frac{u^*-\langle u^*\rangle}{\langle u^*\rangle},\quad Pe = \frac{\langle u^*\rangle h^*}{D^*},\quad \beta = \frac{\beta^* h^*}{D^*},\quad C = \frac{\langle u^*\rangle h^{*3}}{D^* Q^*}C^*, \tag{8}$$

where x is the longitudinal coordinate moving with the mean speed of the stream, Péclet number (Pe) quantifies the relative importance of advection and effective diffusion, u stands for the velocity deviation from its mean.

Then the governing equation and the initial and boundary conditions are rewritten as

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{\partial^2 C}{Pe^2\partial x^2} + \frac{\partial^2 C}{\partial z^2}, \tag{9}$$

$$C(x,z,0) = \delta(x)\delta(1-z), \tag{10}$$

$$\frac{\partial C(x,1,t)}{\partial z} = 0, \tag{11}$$

$$\frac{\partial C(x,0,t)}{\partial z} = \beta C(x,0,t), \tag{12}$$

$$C(x = \pm\infty,z,t) = 0. \tag{13}$$

We also use the bar to denote the variables related to the cross-sectional mean concentration $\langle C\rangle$, and

$$\overline{C} = \langle C\rangle. \tag{14}$$