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Measurement of mass diffusivity by light streak imaging

Yogesh M. Nimdeo[a], Yogesh M. Joshi[a,*], K. Muralidhar[b]

[a] Department of Chemical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

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ABSTRACT

Mass diffusion relates to migration of one species in another and is a consequence of local heterogeneity of concentration distribution and energy. The present study describes an optical method based on the shadowgraph technique for measuring a binary mass diffusivity of a solute in a solvent using a collimated beam of light. The measurement technique exploits the principle that refraction of a light beam due to concentration gradient creates a sharp visible streak in an image. The streak is a bright, visible linear feature in a shadowgraph image and opens up a new method of diffusivity measurement. The movement of the streak with time is due to a finite mass diffusivity of a solute in a solvent. Experiments with glucose, salt and glycerin diffusion in water have been conducted within a time window obtained from the sensitivity analysis. The respective mass diffusivities are determined by the light streak as well as the linearized shadowgraph technique, and compared with the values reported in the literature. The proposed approach promises to yield a simple method of determining mass diffusivity in a variety of binary systems without explicit measurement of the species concentration.

1. Introduction

Determination of mass diffusivity in binary systems is essential for widespread applications such as dispersion of contaminants, mass transfer phenomena with chemical reactions, dissolution process of a solid phase in a solvent, and in many pharmaceutical and biotechnological applications. Furthermore, modeling and analysis of engineering processes often require the knowledge of mass diffusivity. The conventional methods of measuring mass diffusivity in the binary diffusion systems are elaborate and time consuming. Most require the measurement of species concentration that by itself is a difficult task. In addition, measurement techniques often intrude the diffusion process thereby inducing errors in the measurements. Many obstacles in the estimation of mass diffusivity can be overcome by employing optical techniques owing to their inertia free and nonintrusive nature. Moreover, since refractive index is very sensitive to change in density (or concentration of species), optical techniques allow very accurate determination of concentration field. In this work we demonstrate use of an optical technique based on shadowgraph to determine mass diffusivity of a binary system. While shadowgraph accurately determines mass diffusivity it requires sufficiently powerful laser source and high resolution imaging techniques to precisely measure the refractive index variation in the diffusion field, and is also time consuming. To address this issue we propose a novel method based on light streak imaging which allows rapid determination of mass diffusivity by using commonly available white light and low resolution image grabber.

In the literature many methods have been employed to estimate mass diffusivity. One of the most commonly employed technique is the Stokes type of diaphragm cell wherein quasi-steady state diffusion occurs through a porous diaphragm (Cussler, 2009; Stokes, 1950). Here, diffusion takes place through a porous barrier (diaphragm) connecting two

* Corresponding author. Tel.: +91 5122597993; fax: +91 5122590104.
E-mail address: joshi@iitk.ac.in (Y.M. Joshi).
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cells, which are maintained initially at distinct but uniform liquid concentration by stirring. A sintered glass piece or filter paper may be used as diaphragm. After a known time interval, concentration is measured in both compartments, which leads to estimation of mass diffusivity. The decaying pulse technique takes advantage of the transient behavior of a semi-infinite system subjected to a concentration pulse of a limited duration at its boundary (Capobianchi et al., 1998). The mass diffusivity is determined by analyzing the pulse movement against the appropriate analytical solution.

Mass and thermal diffusivity, particularly in biological tissues and porous media have been measured using radiation techniques. These media are non-transparent and the measurements of species concentration and temperature are based on scattering (Blagoveshchenskii et al., 2012; Georgalis et al., 2012). Interferometry [Mach–Zehnder (Ahadi et al., 2014; Nimdeo et al., 2014; Riquelme et al., 2007), Rayleigh (Miller et al., 1988; Zhang and Annunziata, 2008), Gouy (Vitagliano et al., 2005), speckle pattern (Kaunisto et al., 2011), holographic (Axelsson and Marucci, 2008), and Michelson (Abramov et al., 2007)] are optical methods in which an unsteady refractive index profile in a transparent system is measured, thus making it particularly useful for aqueous solutions. Concentration can be easily measured because of a unique relationship between density and refractive index. In a Mach–Zehnder interferometer, a beam of light passes through a density or refractive index field formed by diffusion of solute. Consequently there is a phase lag in the light beam passing through the test cell as compared to the reference beam passing through the reference cell. The phase difference results in interferograms containing fringe patterns leading to concentration/refractive index distribution. Measured concentration distribution in space and time is correlated to mass diffusivity through a one dimensional analytical model. The accuracy of such experiments is high but the method is affected by complexity in experimentation, need for high quality optics, stringent alignment conditions, and high cost.

In a beam deflection technique, the light intensity distribution emerging from the test cell changes with time due to continuous diffusion causing change in the refractive index gradient. Such images can be used to determine the time dependent deflection angle of light at the exit plane of the test apparatus to quantify the mass diffusivity. Optical methods have an obvious advantage of not requiring direct species concentration measurement. However, accuracy of parameter estimation depends on resolution of the intensity measurement and hence the bit resolution of a CCD camera (Ambrosini et al., 2008; Königer et al., 2009; Mialdun and Shevtsova, 2008).

The approach proposed in this study for mass diffusivity measurement is related to the shadowgraph technique. In the proposed technique, a light streak formed on the screen is located and followed in a pre-defined mass transfer process. This information relates in a simple manner with the mass diffusivity. Neither phase nor intensity is required in the data analysis. Hence, unlike measurements based on coherent optics, it does not require a laser, laser-grade optics, or a high resolution detector for light intensity measurement. Streak formation is related to beam deflection and occurs even with a white light source. The entire approach is robust, cost-effective, and is ideal for creating a portable instrument. There are several implications of working with an image feature and not the intensity distribution. The light streak is bright and clearly identifiable. Its position can be determined by feature extraction techniques and light intensity itself need not be

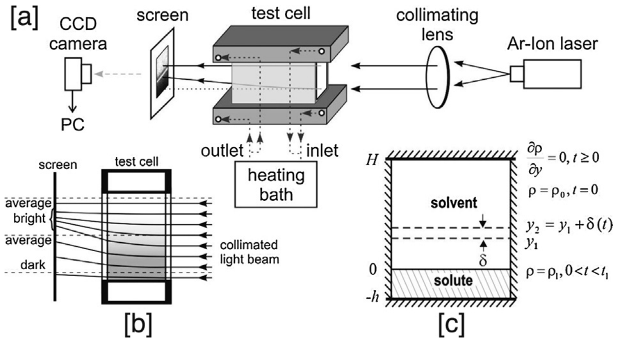

Fig. 1 – Schematic drawing of (a) Experimental setup for light streak imaging. (b) Passage of a light beam through a field of concentration gradient and formation of the streak of light, and (c) initial condition inside the diffusion cell.

measured. Therefore, inexpensive detectors such as photodiodes or digital cameras can be used. Moreover, data analysis is simpler than in the original shadowgraph method.

2. Description of the diffusion field

The schematic diagram of the diffusion field is shown in Fig. 1c. Here, H is the height of the solvent placed over the solute having height h. If a mass diffusion coefficient D is assumed to be a constant, the time dependent concentration profile along the vertical coordinate (y) of the test cell is obtained by applying Fick's second law of diffusion for the density distribution $\rho(y, t)$ (Bird et al., 2009):

$$\frac{\partial^2 \rho}{\partial y^2} = \frac{1}{D}\frac{\partial \rho}{\partial t} \qquad -h < y < H, \quad t > 0 \tag{1}$$

If ρ_1 and ρ_0 are the respective densities of the solute and the solvent, an initial condition is given by

$$\rho = \rho_0 \qquad 0 < y < H \quad \text{at} \quad t = 0, \tag{2}$$

and

$$\rho = \rho_1 \qquad -h < y < 0 \quad \text{at} \quad t = 0 \tag{3}$$

The boundary conditions at the impermeable top and bottom surfaces of the cavity are

$$\frac{\partial \rho}{\partial y} = 0 \qquad \text{at} \quad y = H \quad \text{and} \quad y = -h \tag{4}$$

Eq. (1) can be solved analytically for initial conditions given by Eqs. (2) and (3), and the boundary conditions given by Eq. (4). The solution suggests that for $t > 0$ the concentration at the interface drops from ρ_1 to $(\rho_1 + \rho_0)/2$ almost instantaneously and remains constant for a prolonged period of time (Nimdeo et al., 2014). Consequently, the problem can be solved by considering a constant concentration boundary condition at the initial solute–solvent interface ($y = 0$) over $0 \le y \le H$ with a boundary condition given by

$$\rho = \frac{\rho_1 + \rho_0}{2} \qquad \text{at} \quad y = 0 \quad \text{for} \quad t \ge 0 \tag{5}$$