Experimental study of the effect of air oscillations on vapor diffusion in a channel of variable cross-section and in a granular medium

Denis Polezhaev and Victor Kozlov

Perm State Humanitarian Pedagogical University, Laboratory of Vibrational Hydromechanics, Russian Federation, 614000, Perm, 24, Sibirskaya Str.

E-mail: polezhaev@pspu.ru, kozlov@pspu.ru

Abstract. The diffusion of 2-propanol vapor in the air in a channel of variable radius and in a porous medium composed of spheres of equal diameter under longitudinal oscillations is experimentally studied. In the experiments, vapor concentration at the top and bottom of the channel (or porous medium) is constant. In the absence of oscillations, mass transfer along the channel (or porous medium) is carried out due to molecular diffusion. When air oscillations are imposed, additional mass transfer effects are activated, namely, Taylor dispersion and convective mass transfer due to steady vortex flows. In the studied range of frequencies and amplitudes, the total mass transfer exceeds molecular diffusion by one order of magnitude. In a channel of variable radius, mass is transferred mainly due to the steady vortex flows (convective mass transfer) arising in the viscous boundary layer due to the inhomogeneity of the amplitude of air oscillations in narrow and wide sections of the channel. In a porous medium, Taylor dispersion plays a major role while the convective mass transfer makes minor contribution.

1. Experimental technique for the study of vapor diffusion of 2-propanol in air

Diffusion rate of fluid vapor along the axis of the channel is studied experimentally in the vertical axisymmetric tube 1 of length $L = 440$ mm (Fig. 1a). The tube consists of 3 sections. The radius of each section varies in the range from $R_1 = 9.5$ mm to $R_2 = 12.5$ mm; the section length $l = 105$ mm. A schematic illustration of the channel section is shown in Fig. 1b. The porous medium consists of randomly packed hard spheres (radius is 1.45 mm); its thickness is equal to 60 mm (Fig. 1c).

The longitudinal air oscillations are generated by the acoustic louder 2. The acoustic louder provides oscillations of a volatile fluid in the cavity 3 of inner diameter 40 mm and height 40 mm with use of the rod 4 connected with the flexible rubber membrane 5. The upper part of the cavity 3 is coupled with the partially filled with fluid transparent glass cell 6 with inner radius $r = 11.5$ mm and height $H = 40$ mm.

When vapor diffusion in the channel of variable diameter is studied, the channel 1 is coupled to the rubber 7 and then to the transparent glass cell 6. When mass transfer through the bed of randomly packed hard spheres is studied, a grid is inserted into the transparent glass cell (above the free surface of
evaporating fluid), onto which glass beads are placed. The oscillations of the flexible membrane initiate the fluid oscillations in the transparent cell and air oscillations in the tube or in the pores between hard spheres. The temperature of the bronze cavity is maintained constant with an accuracy of 0.1°C by a ring copper heat exchanger (not shown in Fig. 1), connected to the circulation thermostat LOIP LT-316. The handling of the acoustic louder is carried out by a digital generator ZETLAB and an amplifier Digisynthetic DP3200. The electrical signal of the generator is transmitted to the amplifier and then to the acoustic louder.

The frequency of the imposed fluid oscillations vary in the range $f = 10 – 90$ Hz. The amplitude of the fluid oscillations $b_f$ is measured with use of DSLR camera Canon EOS 60D with Canon Lens EF-S 35 mm f/2.8 IS STM Macro Led, placed in front of the glass cell and focused on the interface between the fluid and air.

Since 2-propanol evaporates, the height of the fluid column decreases, which allows measuring the volume of evaporated fluid and, therefore, the diffusion kinetics of vapor. The equation for the coefficient of molecular diffusion in a channel of variable radius has the following form:
Here $D$ is the diffusivity of vapor in air, $\rho$ is the density of fluid 2-propanol, $\rho_0$ is the density of vapor 2-propanol, $dh/dt$ is the displacement rate of the fluid free surface.

In the experiments with porous medium, vapor diffuses through the pores between randomly packed glass spheres. The randomly packed spheres give a porosity of about $P = 0.40$ (see, for example, [2]). Then, the area of air pores in each plane of the porous medium differs from the surface area of the fluid by a factor of $P$, and Eq. (1) can be rewritten in the following form:

$$ D = \frac{r^2}{R^2} \frac{dh}{dt} \frac{\rho}{\rho_0} L. $$

(2)

2. Experimental results

Figure 2 illustrates the time evolution of the free surface position due to evaporation in the channel of variable radius. In the absence of fluid (and air) oscillations, the height of the fluid column decreases with a rate of $5.5 \times 10^{-6}$ mm/s (Fig. 2a). When fluid oscillations are applied, the intensity of mass transfer increases markedly – the free surface velocity is equal to $33 \times 10^{-6}$ mm/s in Fig. 2b. The scattering of experimental data in Fig. 2b is due to the fact that the digital generator and DSLR camera are not synchronized and therefore images of the free surface are captured at various phases of the fluid oscillations. Thus, mass transfer in oscillating air increases several times compared to molecular diffusion $- D_{\text{eff}}/D >> 1$.

Similar measurements of vapor diffusion were carried out in the experiments with randomly packed hard spheres (Fig. 3). It is found that the height of the fluid column in the experiments with oscillating fluid (and air) decreases faster than in the experiments without oscillations. The intensification of mass transfer in a channel of variable radius and in a porous medium is explained by the combined effect of both Taylor dispersion [3] and averaged vortex flows [4].
The efficiency of Taylor dispersion can be estimated from the equation obtained for a straight channel of constant radius:

\[ D_{\text{eff}} = D(1 + \gamma Pe^2), \]  

(3)

here \( D_{\text{eff}} \) is the vapor diffusion coefficient in oscillating air, \( Pe \equiv 4\pi b_{\text{air}}R^2/\nu \) is the Peclet number (\( b_{\text{air}} \) is the amplitude of air oscillations in wide sections of the channel, \( \nu \) is the air kinematic viscosity), parameter \( \gamma \) depends on dimensionless frequency of air oscillations \( \omega \equiv 2\pi f R^2/\nu \) and Schmidt number \( \sigma = \nu/D \). In equation (3), the first term characterizes molecular diffusion; the second term characterizes the Taylor dispersion. Earlier it was found [3] that at \( \omega \sim 1 \) the parameter \( \gamma = \sigma/192 \) and it decreases according to the law at \( \gamma \sim \omega^{-3/2} \) at \( \omega > 1 \).

The results of calculating the coefficient of effective diffusion in a channel of variable radius are shown in Fig. 4a. Empty symbols illustrate experimental data; filled symbols illustrate calculations of \( D_{\text{eff}}/D \) by Eq. (3). One can find that Taylor dispersion is weak, and this effect is not able to substantially enhance the rate of vapor diffusion. Recently it was experimentally found that enhanced vapor diffusion in a channel of variable radius can be explained the excitation of steady vortex flows due to the inhomogeneity of the amplitude of air oscillations in narrow and wide sections [4].
Let us consider the method for calculating the diffusion coefficient in a porous medium. The air flows through the randomly packed spheres along tortuous paths of interconnected pores. Tortuosity $\tau$ is one of the commonly used parameters for describing pore geometry. It is defined as the ratio of the actual length of the flow path over the thickness of porous medium. Consequently, the experimental value of the diffusion coefficient is $\tau$ times less than the molecular diffusion coefficient. According to the experiments in the absence of air oscillations, $\tau_{exp} = 1.43$.

**Figure 3.** Evolution of the free surface position due to evaporation in the porous medium: (a) without oscillations at 28°C; (b) in the presence of oscillations, $f = 30$ Hz, $b_f = 0.29$ mm at 20°C

**Figure 4.** Dimensionless effective diffusion coefficient $D_{eff}/D$ versus Peclet number. (a) The channel with periodically varying radius: Experimental results (empty symbols); theoretical predictions for obtained
Peclet numbers \( D_{\text{eff}}/D = 1 + \gamma(\text{Sc}, \omega)Pe^2 \) [3] (filled symbols). (b) The porous medium: Experimental results (empty, filled, and semi-filled symbols); theoretical predictions of Taylor dispersion theory (solid, dashed and dash-dotted lines).

In order to verify the result obtained, \( \tau_{\text{exp}} \) was compared with theoretical predictions. Comiti and Renaud [5] proposed the following equation for the tortuosity:

\[
\tau = 1 - \lambda \ln P, \quad (4)
\]

here \( P \) is the porosity (it was discussed above that \( P = 0.40 \) for randomly packed spheres), parameter \( \lambda \) depends on the shape of particles. For beds of spheres, \( \lambda = 0.49 \) [6]. Then, calculations by Equation 4 give \( \tau_{\text{theor}} = 1.45 \), i.e. experimental data agree well with theoretical predictions. In accordance with the above reasoning, Eq. (3) for evaluating the efficiency of Taylor dispersion should be rewritten in the following form:

\[
\tau D_{\text{eff}} = D(1 + \gamma Pe^2), \quad (5)
\]

where Peclet number and dimensionless frequency of oscillations are the functions of hard spheres radius.

Figure 4b illustrates the experimental results (empty, filled and semi-filled circles) and calculations by Eq. (5) (solid, dashed and dash-dotted lines) for randomly packed spheres. It is obvious that experimental results and predictions of the theory of Taylor dispersion are in good agreement with each other.

Thus, the vapor diffusion is enhanced by Taylor dispersion, while the effect of steady vortex flow is negligible. The insignificant contribution of averaged vortex flows to the mass transfer is explained by the fact that the secondary flow velocity depends on dimensionless frequency of oscillations [4]. At \( \omega \sim 1 \), dimensionless velocity is small and linearly increases with dimensionless frequency.

3. Conclusion
The vapor diffusion of 2-propanol in air in a channel of variable radius and in a porous medium consisting of randomly packed hard spheres is experimentally studied. It is found that vapor diffusion can be intensified by air oscillations. In a channel of variable radius, the enhanced mass transfer occurs due to averaged vortex flows generated due to the inhomogeneity of the amplitude of air oscillations in narrow and wide sections of the channel. In a porous medium, mass transfer is enhanced due to Taylor dispersion. The negligible effect of averaged flows on mass transfer is explained by the fact that these secondary flows are weak in the limit of low dimensionless frequencies.

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