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Enhanced vapor diffusion inside the circular tube of variable cross section

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Abstract. The effect of high frequency oscillations of air column in a channel of variable cross section on vapor diffusion is experimentally studied. It is found that significant enhancement of longitudinal mass transfer takes place due to steady vortical flow excited in channel sections. In parallel with experiments in air we conducted PIV experiments with low viscous fluids in order to study the steady flow field in the same range of dimensionless frequency as in diffusion experiments with air. It is revealed that additional mass transfer associated with the steady flow is a function of steady flow dimensionless velocity *V*, which depends on frequency and pulsating Reynolds number. Comparison of experimental data obtained in the channels of various geometries shows that increase of variation of a channel radius results in significant enhancement of steady flow velocity and, therefore, mass transfer.

Diffusion rate of liquid vapor along the axis of the channel is studied experimentally in the vertical axisymmetric tube *1* of length L = 440 mm (**Fig. 1a**). The channel is made of a Plexiglas plate with flat surfaces to reduce optical distortion in the experiments for flow structure visualization. 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**.

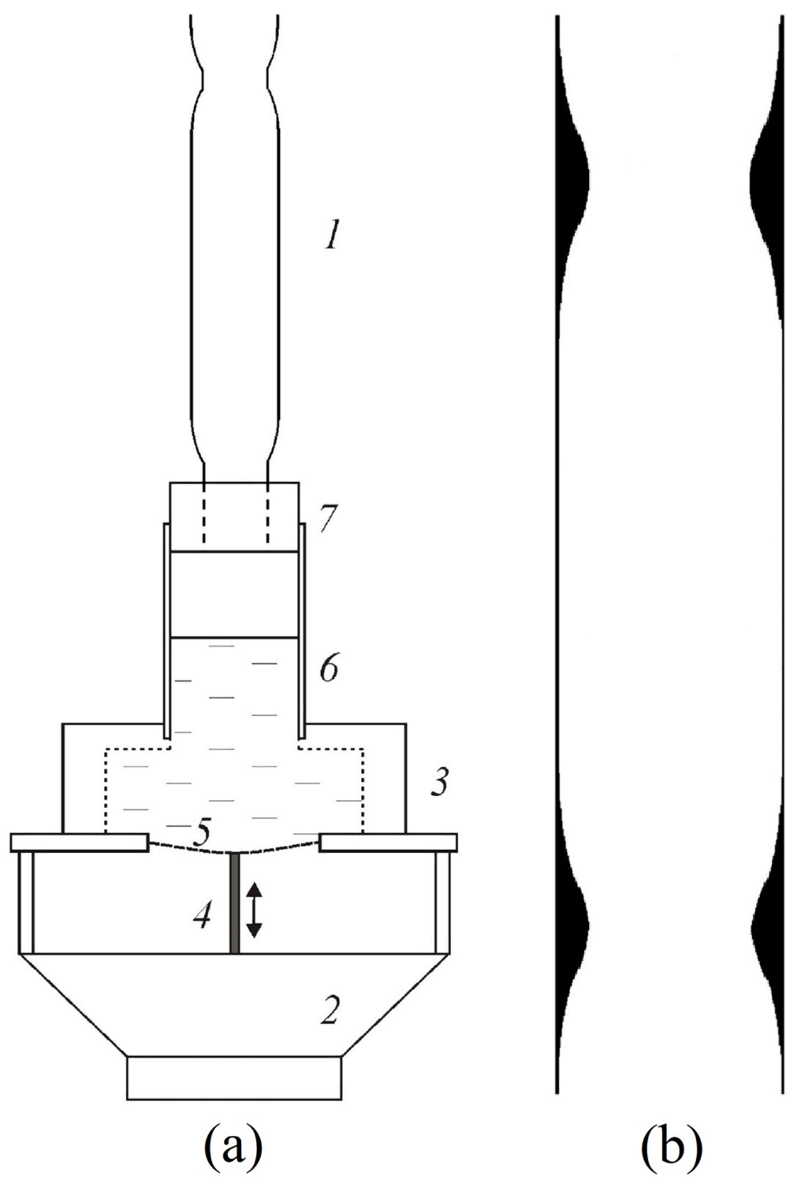

Fig. 1. (a) Sketch of the experimental setup.
(b) Shape of the channel section

The longitudinal oscillations of the air column in the channel 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. The glass cell is connected with the tube *1* by means of the rubber plug *7*. The oscillations of the flexible membrane initiates the fluid oscillations in the transparent cell and air oscillations in the tube *1*. The transparent cell *6* is used to measure the evaporation rate of the fluid: the upper end of the tube *1* is open, as fluid evaporates, the height of the fluid column decreases, which allows to measure the volume of evaporated fluid and, therefore, the diffusion kinetics of vapor. The experiments are conducted using 2-propanol. The frequency of the imposed fluid oscillations vary in the range f = 40 – 90 Hz. The amplitude of oscillations varies in the range b_f = 0 – 0.38 mm. The protocol for each experiment is the following. The temperature of the thermostat is set to 23ºC which is close to the ambient temperature. Then, the fluid oscillation of the desired frequency and amplitude is initiated. The free surface of 2-propanol in the transparent cell is clearly visible and its distance h_f from the bottom end of the channel with periodically varying diameter can be readily obtained by image processing.

The diffusion coefficient can be obtained from the equation

$$D = \rho_f \frac{dh}{dt}\frac{L}{\rho_0},$$

here $\frac{dh}{dt} = \frac{dh_f}{dt}\left(\frac{r}{R_2}\right)^2$ is the velocity which fluid would have if it evaporates in the same channel in which its vapor diffuses. It is revealed that free surface descending velocity *dh*/*dt* significantly increases in the presence of oscillation. The effect of the oscillation amplitude *b* on evaporation rate is shown in **Fig. 2**. At once, the increase of frequency *f* results in the enhancement of evaporation rate.

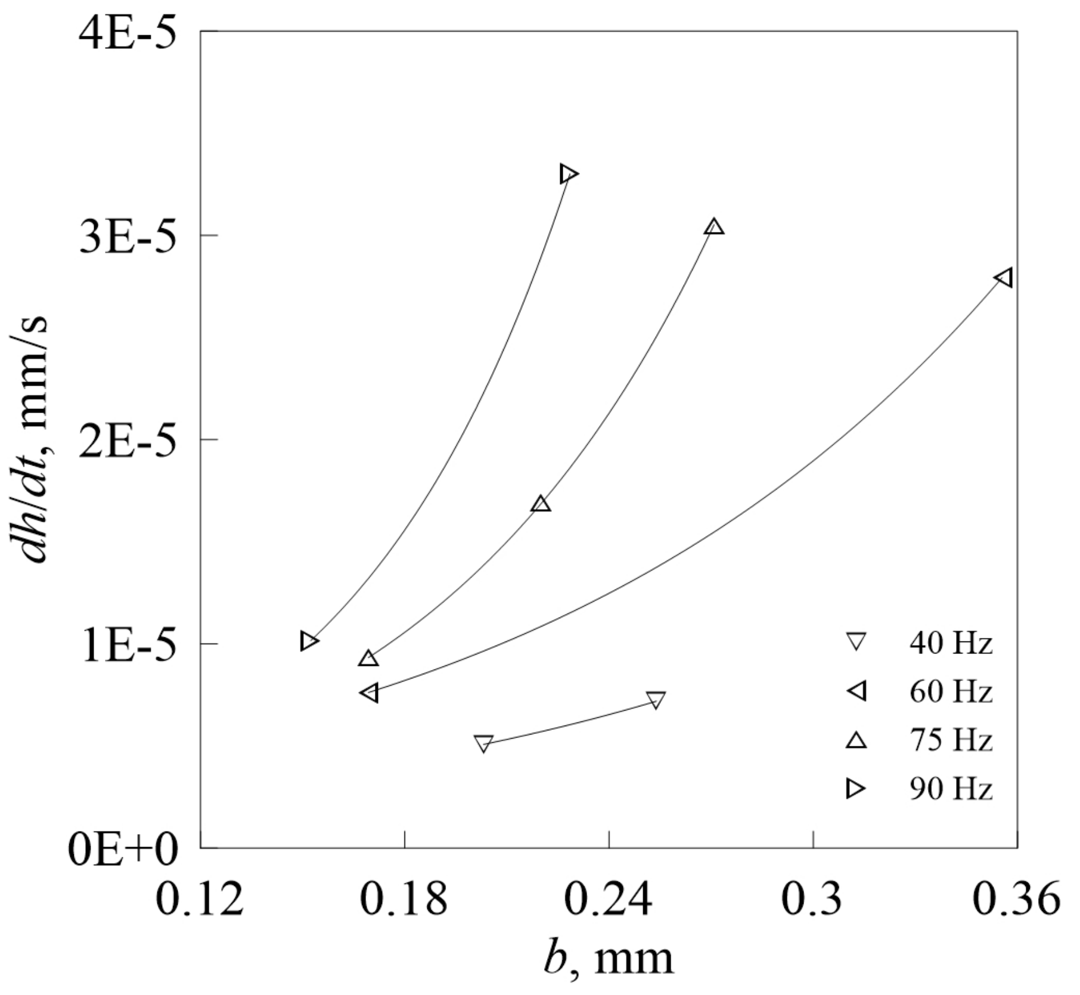

Fig. 2. The free surface velocity as a function of the amplitude of air oscillations for various frequencies

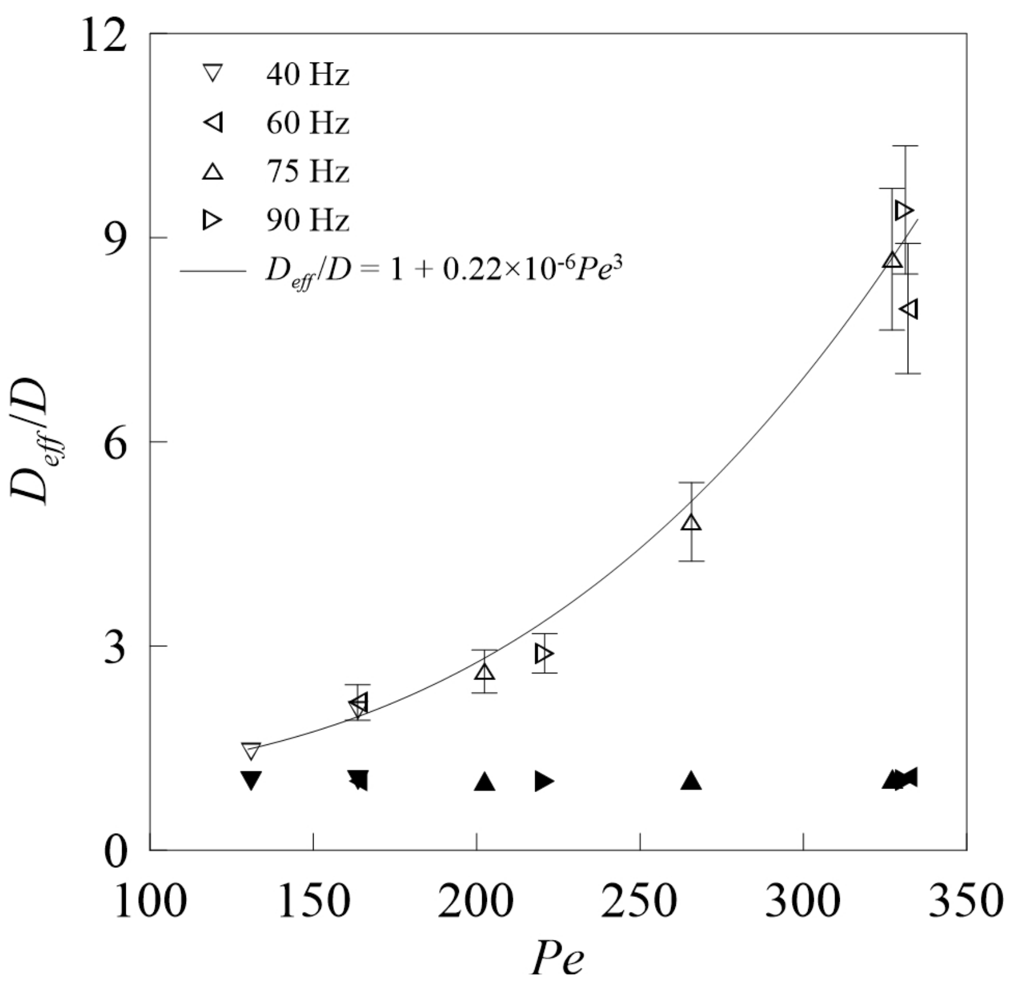

Fig. 3. Effective diffusion coefficient D_{eff}/D versus Peclet number: Experimental results (empty symbols); theoretical predictions based on Taylor dispersion (filled symbols)

Thus, we see that air oscillations lead to intensification of the fluid evaporation or, in other words, to an increase of the rate of longitudinal vapor diffusion in a vertical channel of alternating diameter. The positive effect of gas oscillations on the diffusion rate of passive contaminant was previously observed in straight channels: When a fluid flows through a tube, a velocity profile develops in the transverse direction: the fluid moves faster in the center than near the tube wall. Such transverse gradient of the longitudinal velocity initiates the longitudinal dispersion. This phenomenon is known as Taylor dispersion.

Figure 3 shows the experimental results in the plane of dimensionless parameters *Pe*, D_{eff}/D in order to assess the effect of Taylor dispersion on the enhancement of evaporation rate of 2-propanol in the channel of alternating cross section.

Here Peclet number $Pe = \frac{4\pi f b_f r^2}{R_2 D}$.

The experimental data obtained at various frequencies of oscillations agree well with each other and obey the law $D_{eff}/D \sim Pe^3$. In the studied range of the Peclet number, air oscillations can increase the diffusion rate by one order of magnitude. Filled symbols represent the data obtained from Taylor dispersion. It is obvious that the Taylor dispersion cannot explain the enhancement of mass transfer of vapor 2-propanol in the channel of alternating cross section.

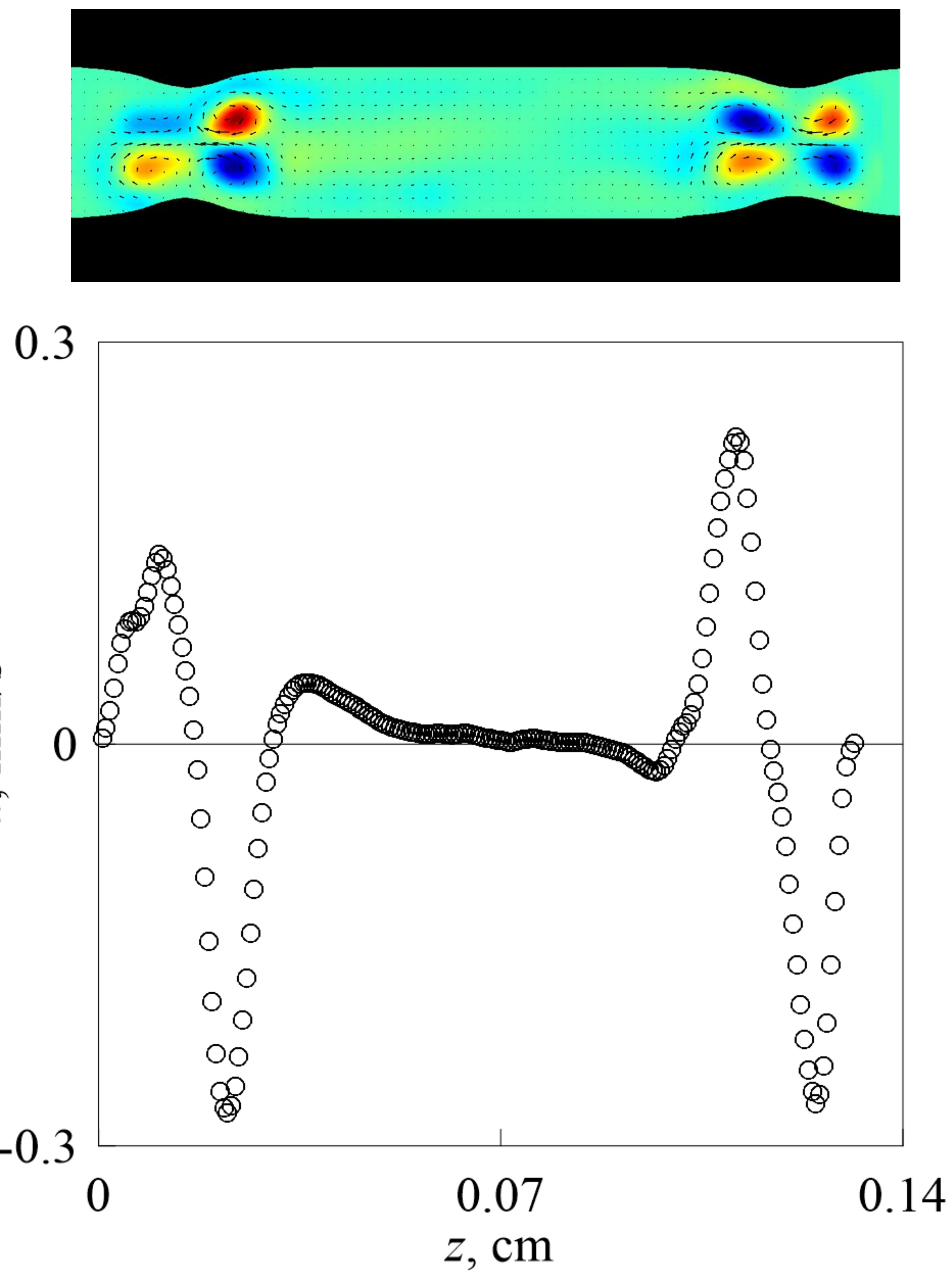

Fig. 4. The axial component of the steady flow velocity as a function of coordinate z at the axis of the channel. Axial positions z of peak velocities correspond to the centers of vortices: Two central peaks indicate the positions of vortices in the central section of the channel; the leftmost peak indicates a vortex center in the left section, the rightmost peak indicates a vortex center in the right section

We believe that intensification of longitudinal diffusion in the channel of alternating radius is associated with the generation of steady air vortical flows. In a channel of variable radius, the peak velocity of the oscillatory motion depends on both radial and axial coordinate. Due to the equality of air flow in a narrow and a wide parts of the channel, the peak velocity of oscillatory air flow has the largest value in a narrow part, and the smallest value in a wide one. The spatial inhomogeneity of the oscillation peak velocity in the Stokes layer results in the excitation of steady flow directed towards the positions where the peak velocity is a minimum.

One way to test the hypothesis of the existence of a steady vortical flow, therefore, is to conduct PIV experiments to study fluid flow (**Fig. 4**).

Axial fluid oscillations lead to the onset of steady vortical flow in each cell of the channel. Here, we see that vortices are mainly located near the narrow sections of the tube and are directed from the wide sections to the narrow ones near the axis of the channel. Vlasova et al. (2020) studied the fluid flow in a wide range of dimensionless frequency and found that the increase of ω resulted in both enhancement of vortical flow and change of its direction (**Fig. 5**).

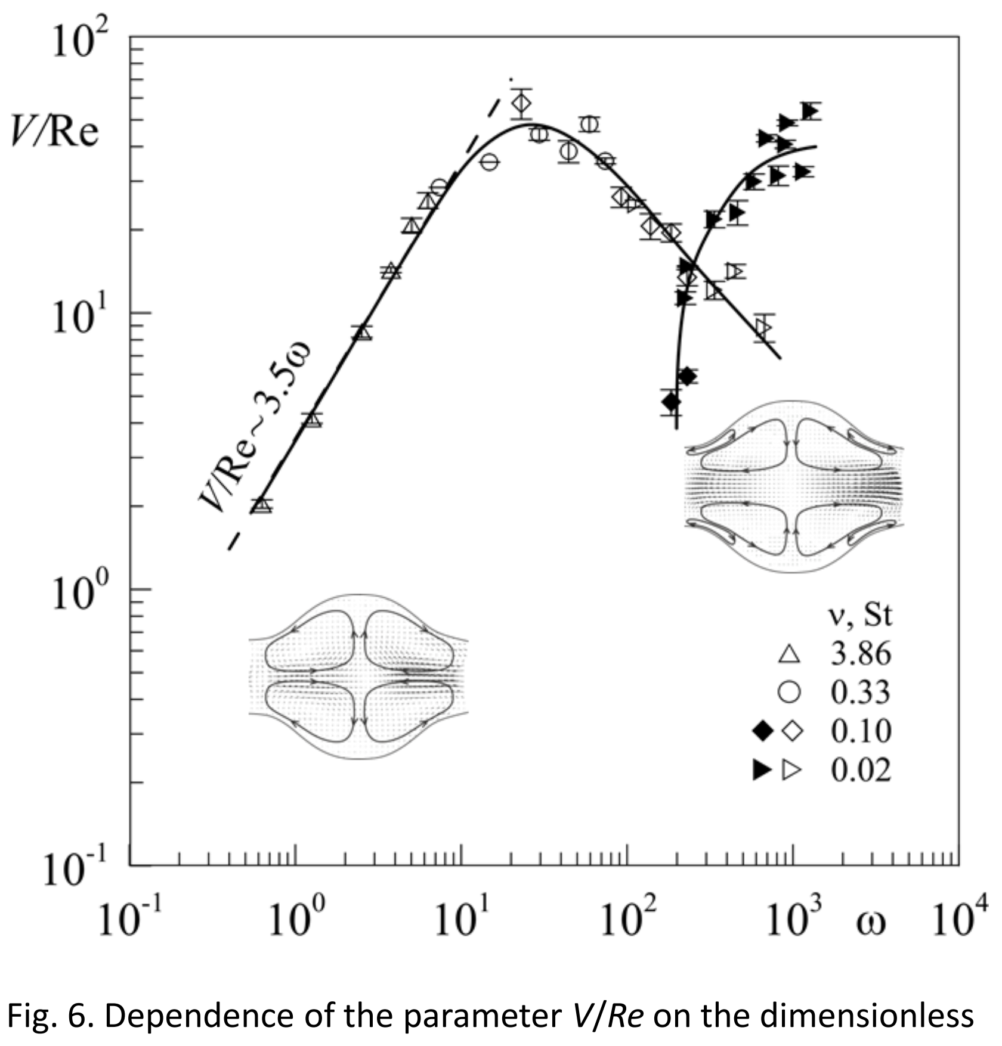

Fig. 6. Dependence of the parameter *V*/*Re* on the dimensionless frequency ω (from Vlasova et al. (2020))

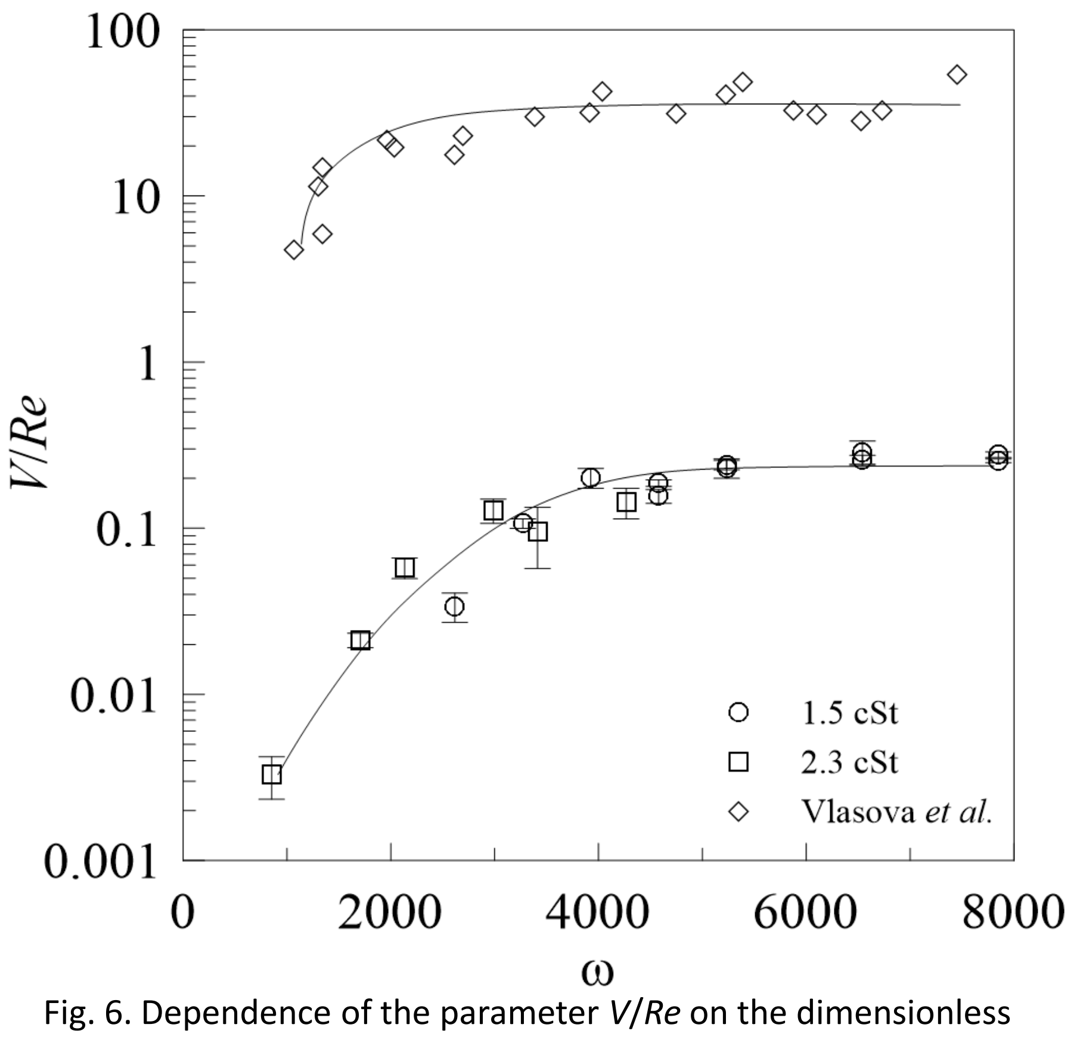

Fig. 6. Dependence of the parameter *V*/*Re* on the dimensionless frequency ω. Circles and squares: Present study; Diamonds: Vlasova et al. (2020)

In the limit of low frequencies ω, they observed primary vortices located near the tube walls and directed to the section center near the axis of the channel. In the limit ω > 10^3, the vortices diminish and are located inside the Stokes layer. Beyond the Stokes boundary layer, these primary vortices induce the secondary vortical flow of the opposite direction of rotation. In the present study, the Stokes layer thickness is less than 1 mm and primary vortices are almost invisible (**Fig. 4**).

Figure 6 shows the intensity of the steady fluid flow in the plane of variables ω and *V*/*Re* ($V \equiv uR_2^2/\nu$ is the dimensionless velocity of the steady flow; $Re \equiv 2\pi f b^2/\nu$ is the pulsating Reynolds number) for secondary vortices inside cells of nearly spherical shape (diamonds) and in the studied channel (circles and squares). Comparison of experimental data shows that increase of radius variation results in significant enhancement of steady flow velocity and, therefore, mass transfer.

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