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Procedure for determining the dye solution concentration distribution in laminar water flow in glass channel

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Abstract. An experimental technique has been developed aimed at determining a dependence of the distribution of Rhodamine G concentration in a water solution flow in a glass channel. It has been demonstrated that in the water flow moving in the glass channel, a stationary pattern of the distribution of solution concentration in water along the channel is established. The dye concentration is distributed uniformly over the channel due to molecular diffusion.

1. Introduction

In recent years, the study of flows in small tubes and channels has been of increasing interest in different fields. A decrease in the sizes of tubes and channels resulted in the creation of the so-called microfluidic devices. The investigation of microfluidic systems can be used in many practical applications, such as micromixers, cooling circuits in microsystems, diagnostics systems of biological objects, and others.

A.E. Kamholz and P. Yager [1,2] were one of the first to research diffusion in laminar flows in T-type microchannels. Their studies present the numerical modeling of solution diffusion in a pressure-driven flow. One part of these researches characterizes the law of diffusion scaling by the device width which allows predicting precisely the true spatial distributions of diffusing molecules. The other part of these studies simulates the measurements performed using a T-channel and determines quantitatively how the laws of non-uniform diffusion scaling are distributed when measuring molecular diffusion [2].

T-type channels (Fig. 1) are the most simple in manufacturing and effective form of fluidic devices. In [3], the results of numerical simulation of the process of mixing two liquids in Tchannels with different input and output channel diameters were presented. The authors showed that there are several flow regimes in the T-channel. At small values of the Reynolds number (not more than 50), a laminar flow regime is established in the channel, and the diffusion mixing mechanism is dominant.

The Reynolds number is calculated by the formula:

$$Re = \frac{\rho v D_h}{\nu}$$

where ρ is the density of a liquid; v is the volumetric flow rate velocity in a channel; D_h is the hydraulic diameter; ν is the dynamic viscosity of a liquid.

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Figure 1. Scheme of a T-type channel

The quantitative description of molecular interactions in a microchannel presented in [4] is a simulation tool which considers the geometry of a device, the coefficient and dependence of viscosity, ionic strength, and other environmental factors. The model shown in this research was two-dimensional, and a change in the concentration with the channel length was investigated. The results show with confidence that this model is suitable for the simulation of primary processes in a T-type channel.

The linear problems of diffusion in thin tubes or channels are solved similarly to the methods proposed for solving the problems of heat conductivity in thin rods [5]. Based on this, the equation for the solution of diffusion problem in a thin channel is as follows:

$$c = \frac{c_0}{2} + \frac{2c_0}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{2n-1} \cdot \exp\left(\frac{\pi^2 D(2n-1)^2}{l^2} \cdot t\right) \cdot \cos\left(\frac{\pi(2n-1)x}{l}\right)$$
(1)

where c_0 is the initial concentration, l is the width of a channel, D is the diffusion coefficient.

The present work is devoted to the experimental study of diffusion in laminar flows in glass channels.

2. Experimental procedure

The investigations were performed using an experimental setup shown in Fig. 2. A the glass T-type channel was placed on the stage of an optical microscope; it was fixed with four small magnets. The T-channel had two inlets and one outlet. Two flexible Teflon capillaries with an inner diameter of 0.6 mm were connected to the inlets. A short capillary was connected to the outlet through which the liquid was poured into a small container. At the other side, two input capillaries were connected to syringes with a volume of 2 ml. The syringes were installed on a SPLab02 syringe pump with a volume flow rate in the range between 0.001 μ l/min and 127 ml/min. To record the experiment, the body of a SONY NEX-5R mirrorless camera was installed on a Mikmed-6 optical microscope. Images were taken through the microscope objective at nominal magnification × 10 using the camera. The spatial resolution in the object plane was ~ 1 μ m, and the depth of focus was ~ 10 μ m. The resulting images were processed using different graphics editing programs and Matlab software package. The setup was placed on an optical table with 1VIS10 pneumatic vibration isolation system.

Three slides with smoothly polished faces were used to produce glass T-type channels. One of the slides was cut into three parts to form a T-form. The resulting three parts were placed



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Figure 2. Scheme of the setup: 1 - high-speed camera; 2 - Mikmed-6 optical microscope; <math>3 - glass channel; 4 - syringe pump; 5 - Teflon capillary

between two other uncut slides thus forming a T-form channel and were bonded with UV glue. Apertures were formed on three face surfaces of the chip produced. Capillaries made of stainless steel were glued into the apertures; they were connectors of the chip. A transparent chip with a length of 76 mm, a width of 26 mm, and a height of 3 mm (Fig. 3) resulted. The inner width of the channel was 0.6 mm, the inner height was 1 mm. The length of the channel from two channels junction into one channel, to the outlet was 54 mm. The length of each input channel was 12.5 mm.



Figure 3. Scheme of the chip with the T-type channel

The chip produced was placed on the optical microscope stage. After that, two flows were simultaneously supplied to the channel. The solution of Rhodamine G in distilled water was supplied to one of the channel inlets. Pure distilled water was supplied to the second inlet. The volumetric flow rate varied from 10 to 100 μ l/min. This indicated that a laminar regime was established in the channel. The installed camera allowed recording a flow passing through the channel. The images of the entire channel were taken by moving the stage and by recording

each section/part of the laminar flow in the channel using the camera.

To process correctly the resulting images, the experiment was performed in several stages. After adjusting the camera and light, an image of only the light from a light source under the stage without the installed chip was taken. Then, the channel was placed on the stage, and the empty channel was recorded. The parameters of the camera and illumination remained the same throughout the recording cycles. Then, two flows of pure distilled water were supplied to the channel, and the camera took images of the channel with water. Only after this procedure which was performed for further normalization of the brightness and color of channel images, flows with the dye and water were supplied.

3. Results

The resulting images presented a whole picture formed in the channel by two flows (Fig. 4). In an initial section of the channel where two flows join, a sharp interface between the flows is seen in the image (Fig. 4a). At a distance of about 15 mm from a section where two channels join, the interface still can be observed, but not as clearly as at the beginning of the channel (Fig. 4b). There is no interface at the end of the channel; the solution of Rhodamine G is uniformly distributed over the channel section shown in the image (Fig. 4c).



Figure 4. Images of the channel sections taken by the objective at magnification \times 10: – section where two flows join; b – section of the channel middle; c – section of the channel end

The experiment was performed at room temperature. The images presented in Fig. 4 were taken at an average flow rate v = 0.5 mm/s. The Reynolds number was Re = 0.4.

To determine the dependences of distribution of solution concentration in the flow across the channel, the profiles of image intensities in the middle region of each channel section were taken (Fig. 5). An intensity profile was obtained in the form of a sigmoid which agrees well with [5]. Similarly to Fig. 4, Fig. 5 illustrates three area of the channel. The X axis shows channel width. The Y axis demonstrates intensity of the brightness of the processed image where low values show the channel section with Rhodamine G solution, and high values illustrate that without Rhodamine. The greater the distance from the junction beginning is, the transition section of the sigmoid becomes less steep, and the difference in intensity values decreases.

For better clarity, seven uniformly distant transverse profiles of intensity along the channel length were taken (Fig. 6). One can see how the curve slope changes as the distance from the flow to the joining section increases.

The initial concentration of Rhodamine G in water was $\sim 6.3 \cdot 10^6 \text{ cm}^{-3}$. The diffusion coefficient of Rhodamine in water is $\sim 10^{-6} \text{ cm}^2/\text{s}$. Based on these data, as well as on the values of the parameters of channel size and flow rate, an analytical model of the intensity dependence on the channel width in different sections was developed using Eq. (1) (Fig. 7). As one can see from the presented plots, the experimental result is in a good qualitative agreement with the model.

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Figure 5. Transverse intensities of the channel sections: – section where two flows join; b – section of the channel middle; c – section of the channel end

4. Conclusion

An experimental technique has been developed which allows estimating the distribution of flow image intensity in channels. If one knows an initial concentration of a solution, it is possible to interpret easily the intensity values into the percentage or quantitative content of the solution



 $220 \int_{0}^{1} \frac{1}{10} = 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70^{10^{-2}}$ Length, mm

Figure 7. Model of intensity dependence on the channel width

in a liquid flow. This will provide a full picture of a flow in the channel. Since the parameters of a channel are set preliminarily, one can calculate the diffusion coefficient after calculating an average flow rate and time. The obtained experimental results are in a good qualitative agreement with the model.

The presented technique is not tied to the sizes of the investigated systems. In the future, this will enable studying laminar flows in microchannels.

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