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Experimental Analysis of Wall Flow Pattern and Fluid Shear Stress Effects on Creeping Flow Field in Convergent-Divergent Microchannels

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Abstract

The flow of fluids including micron particles in micro channels and manufacturing microfluidics tools have been one of the important topics in last decades and are utilized in different industries. The research procedure is experimental in this work. The experimental tests are carried out on the flow in a convergent-divergent microchannel having 200 μm height. The utilized experimental method in this research is particle tracking based on the xerography technique, observation, record and data processing. The results showed that the velocity of the particles in Y-direction has a great effect on their motion in the convergent-divergent channel. Study of the particles' sedimentation in different Reynolds showed that it can be eliminated the destructive effect of channel obstruction using convergent-divergent channel which is originated from increasing sedimentation in low Reynolds. The shear stress and velocity gradient are two main factors of the particles' velocity in the convergent-divergent channel. The results showed that the shear stress has an excessive impact on the particles' velocity than the velocity gradient. Moreover, besides the upper and bottom walls, side walls affect the particles' velocity.

Keywords: Solid-Liquid Flow, Convergent-Divergent Microchannel, Particles' Slip Speed, Precipitation.
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1. Introduction

Study of particle transfer in low Reynolds number flows has lots of applications in most of engineering and biological processes such as processing of suspensions, sedimentation, membrane separation, polymerization processes and blood flow. These types of flows particularly occur in the channels having low hydraulic diameter (like micro channels) and/or flows with high viscosity so that they are called Stokes or creeping flow.

Study of Stokes flow was found to be significant by appearance of research fields about microfluidics. Microfluidics are actually fluid transfer processes and suspension two-phase flows in the micro channels with micron dimensions and high aspect ratio. Microfluidic tools have various applications including DNA analysis, identification of pathogens in biosensors, creating pharmaceutical formulations and etc. The most important goal in this current research work in the field of microfluidics is to manufacture of small and portable machines, which are easy to use and also include all the operating units that are desirable and usable. The preliminary research works in the field of microfluidics focused on the particles transfer in the micro channels. The micro channels are microfluidic tools that have high cross-section aspect ratio and the ability for transfer of the suspension particles. This type of equipment can be modeled as the transfer of the particles between two infinitely long parallel plates where the fluid and scattered particles are pumped into the channel via micro pumps and/or electric fields [1-3]. The transfer of suspension flows in the channels with high aspect ratio has lots of scientific and industrial applications. Precipitation of the particles in the inclined channels is one of the industrial applications of these flows where the particles are passed through an inclined channel in the suspension flow. Moreover, the particles having different size are precipitated in the different distances from the channel [4]. Of biological applications of particles transfer in the Stokes flows can be referred to blood flow transfer in capillaries [5-7], cell sorting [8], isolation of cell samples [9, 10] and cell culture in the microfluidic tools [11, 12]. Besides many industrial applications of the microfluidics, study on the behavior of suspensions flows and particles transfer in the micro channels is also important from the point of view of basic science. Knowing how to move spherical and elliptical particles into the parallel channels with low distances can be resulted in improvement and promotion of science knowledge of the fluid mechanic and experimental, analytical and numerical modellings in this field.

Liquid-solid two-phase flows with low Reynolds numbers are one of the most applicable currents in many engineering, biological and pharmaceutical sciences. One of the most important applications of these types of flows is in the microfluidic systems. Microfluidic flows are referred to the flows in which the transfer of the micron-solid particles occurs into the microchannels during a signified test bed. The surface effects of the fluid on the particles are of higher importance than macroscales because of increasing the surface relative to the volume of the particles in such channels. Regardless of numerous studies on the liquid-solid two-phase flows performed at different concentrations on micro-scale in the channels, especially in tubes, the recognition of the hydrodynamic behavior of the particles and the particle-wall interaction is a matter that has been less addressed thus far. Moreover, due to the biological, industrial and medical applications, the particles concentration in the microfluidic flows is regularly diluted and one-sided coupling modeling is used to solve the flow field. Study of literature shows that creeping flow regarding the solid-liquid suspension in a convergent-divergent channel has not been investigated yet. Therefore, the current research was done to overcome this deficiency. For this purpose, water-glycerin suspension containing silica particles was provided and passed through a convergent-divergent channel. The results were compared to the values related to a flat channel. To determine the velocity field and applied forces on the particles, a scanning electron microscopy equipped with xerography system was utilized.

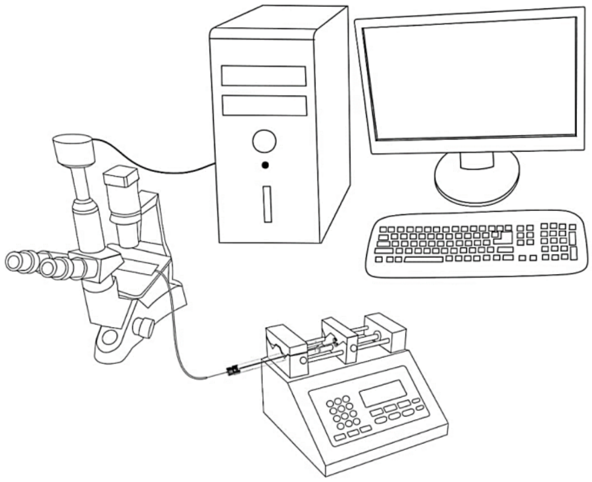

Figure 1: A schematic picture of the test bed used in the current research.

2. Experimental setup

Testbed is provided to observe the hydrodynamic behavior of the micro particles inside the flat and convergent-divergent micro channels based on particle tracking method. This testbed includes three important sections of flow propulsion, suspension production, channel and information registration and observation tools. Schematic of the testbed is shown in the Figure 1.

Observation and data registration section includes an adverse microscope equipped to a camera of a resolution 2 megapixel. The employed syringe pump in the research is a double nozzle syringe pump model SP1000 HOM with a plastic body. (Fanavaran-E-Nano Meghyas Company). The syringe minimum injection velocity is equal to $0.5 \pm 0.005\ \frac{\mu l}{hr}$ 0.5 and its maximum injection velocity is equal to $640 \pm 0.015\ \frac{ml}{hr}$. As the employed channel volume is relatively 62 liters, therefore, it is necessary to use high precision syringes for the injection. As a result, a syringe type made by German Company ILS, No700, Model RN with needle exchangeable capability and a capacity of 1000 μ Liters is utilized. A real image of glass convergent-divergent microchannel and its different parts which are applicated in the current study is respectively shown in Figure 2. The Wet Etching method is used to fabricate these micro channels. The inlet part of this microchannel is a circle with a diameter of 0.2mm which is 5mm distant with respect to the channel port beginning head. After that, the suspension is flown in an inlet chamber and before entering to the channel with 20mm length and 70mm width. This chamber is provided to laminarize and omit all the possible flow turbulences. Afterwards, the flow is flown into a straight channel with 20mm height, and finally is reduced in a divergent section of a length 0.6mm and a width 0.4mm. The design purpose of divergent section is to decrease the area to increase the velocity. The ratio of the straight channel with respect to the convergent channel is 0.4. The flow is then widened with its own convergent conditions. In the next step, the flow is flown through a channel with 35mm length, 1mm width and 200 height and is left from outlet port of the channel which 0.2 mm diameter. Two needles with 0.17mm outer diameter provided and sealed at the channel inlet and outlet. Erection of the needles are as well, so that do not prevent the entrance and exclusion of the flow from the channel.

2.1. Suspension Supply

The purpose of performed experimental tests are to study the behavior of the mono-particle in convergent-divergent microchannel with a rectangular area in a Stock's Regime (Re << 1). The employed suspensions in the current research is water-glycerin solution containing silica particles.

Figure 2: Dimensions of manufactured microchannel in terms of mm (the perpendicular dimension of the plane is 200 μm) and Manufactured microchannel (top view).

Table 1: Test exploited particle specifications

Particle Index of Refraction	Particle Density	Particle Substance	Particle Diameter (dp)
1.59	1.05+0.005	polystyrene	20+0.5

In order to synthesize the suspension, a solution with a weight compound of 19% glycerin and 81% distilled water has been used. The employed particle density values are presented in the Table 1 specifications equivalent to 1.05 $\frac{gr}{cm^3}$, therefore, exploited solution density is intended to be as 1.05 $\frac{gr}{cm^3}$.
In the all tests, suspension viscosity is concerned to be as the same as the glycerin-water solution viscosity equipped to 0.0015 pa-sec.

2.2. The Test Procedure

The holistic test procedure is concerned to be as well that, firstly the suspension solution including silica particle of specified diameter in the glycerin-water solution is dispersed through ultrasonic bath and some of the suspension is sucked into the syringe. Then, the syringe is placed on syringe pump which is the flow propeller and can inject continuous flow at syringe specified flow rates. The syringe needle is connected to the channel inlet, that is located on the adverse microscope, through a polystyrene pipe. The inner diameter of the pipe is equal to the needle outer diameter and consequently the connection of pipe to syringe needle and the channel inlet is nicely sealed without any necessity to use peripheral tools.
Observation and data registration section includes an adverse microscope equipped to a camera of a resolution 2 megapixel, that is installed on the second microscope eye beside the camera software which is installed on a home computer. Microscope operation is as the form that firstly the syringe pump is adjusted in the concerned flow rate and then the injection is started. Syringe pump plunger forces the syringe piston and solid-liquid two phase mixture is injected into the channel through a pipe that is connected to the needle, and is left after completely filling the channel. The microscope that powers the flow in a specified cross-sectional area while the flow is passing through the channel.

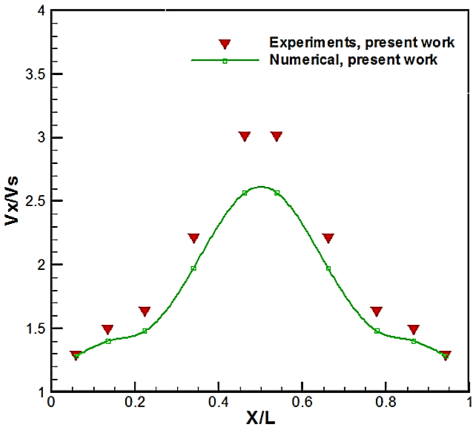

Figure 3: The particle velocity field across the convergent-divergent channel.

Moreover, the images of the powered flow are then recorded by the camera located on the microscope. This camera is connected to computer by a cable, therefore observation, registration and image record is provided in the computer memory.

2.3. Validation

In order to authorize the precision of the machine and the reliability of the studied experimental system, the particle velocity field and the relative velocity of the particle and fluid (slip velocity of the particle) are experimentally determined inside a convergent-divergent microchannel having a height of 200 μm and compared by numerical simulation. The whole results are presented as dimensionless. The distance between center of the particle to the channel inlet (x) and the velocity of the particles in x direction have been dimensionless by the channel length in the convergent-divergent part (L) and the particles' velocity in the channel direct section (V_s), respectively. The results are shown in Fig. 3 and indicate an acceptable accordance between numerical and experimental solution.

3. Results

The experimental data of the velocity of the particles in y-direction for different values of $\frac{d}{H}$ are shown in Figs. 4-6. X-axis is the channel length that is dimensionlessed using convergent-divergent channel length. Y-axis is dimensionlessed based on the velocity in the channel direct section. It should be mentioned that in previous studies [14], the particles' velocity is investigated in x-direction whereas in this research, the y-direction velocity is examined, which has much influence on the particles' velocity value, was scrutinized. Fig. 4 shows the velocity of the particles in y-direction in $\frac{d}{H} = 0.5$. The results indicate that the particles that move though the center of the channel are not under influence of the wall channel and their y-direction velocity is approximately equal to zero. But when the particles arrive at the neck of the channel, due to the fluctuations and being on different velocity gradients (shear stress), the velocity upsurges in y direction by 8 times. Moreover, Figs. 5 and 6 show that as we close towards the upper and lower walls, the velocity of the particle in y-direction in $\frac{d}{H} = 0.6$ and $\frac{d}{H} = 0.8$ has about 21% and 62% enhancement trend, respectively, due to effect of lateral walls on the particle motion.

Fig. 7 shows the velocity of the particles in x-direction in the channel center at different widths ($\frac{d}{W} =$ 0, 0.2, 0.3 and 0.6). The x-axis is the longitudinal distance from the convergent-divergent section inlet which is based on the length of the dimensionless convergent-divergent channel. The y-axis has been dimensionless established upon the velocity in the channel direct section. The results show

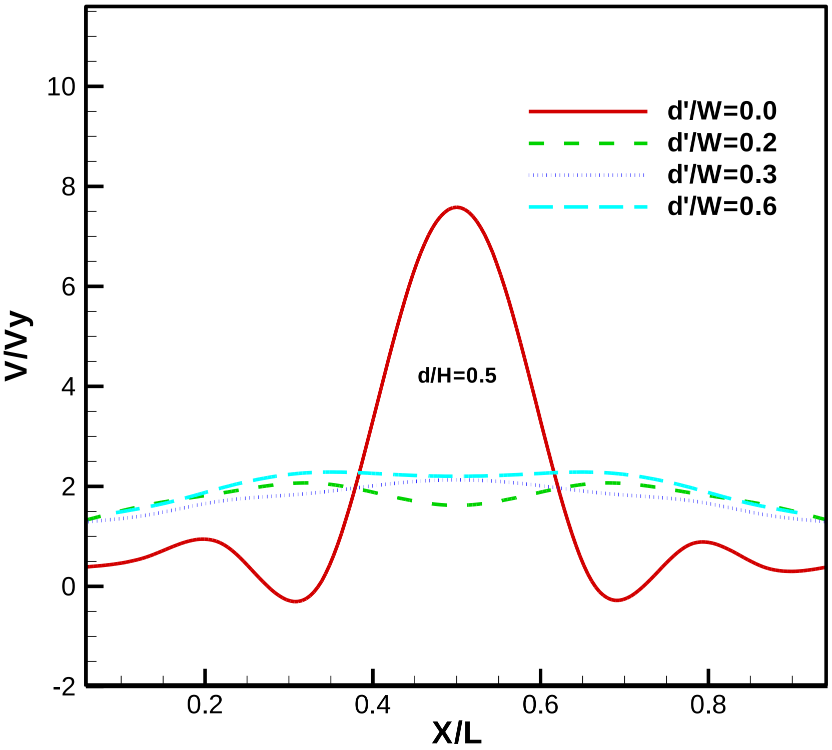

Figure 4: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.5$.

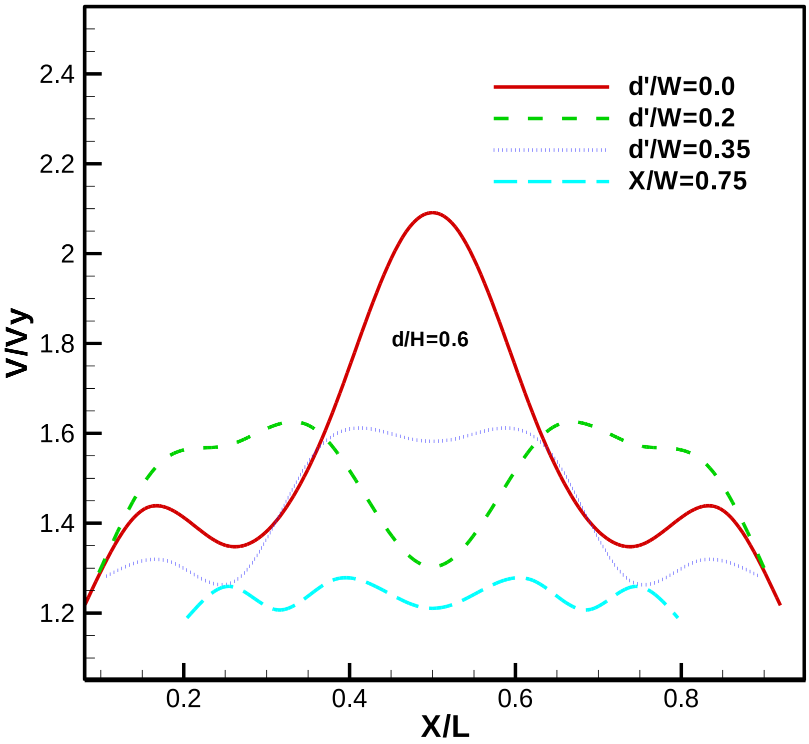

Figure 5: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.6$.

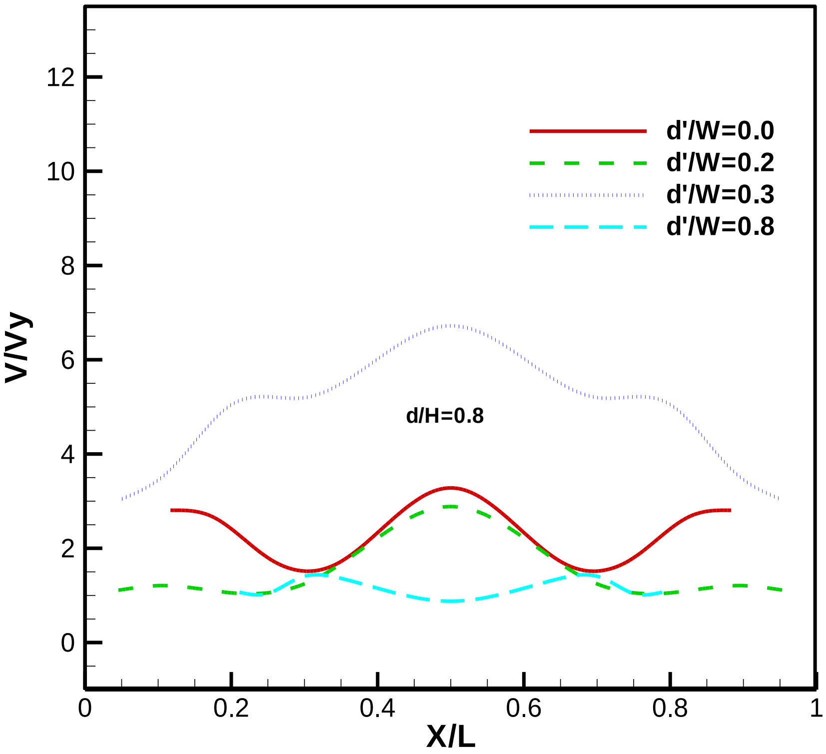

Figure 6: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.8$.

that the velocity of the particles in all areas of the neck is approximately three times more than the particles' velocity in the channel direct section. Consequently, the lateral wall has no effect on the increase rate in the velocity of particles in different widths. Figs. 8 to 10 indicate the velocity of the particles in the x-direction ($\frac{d}{H}$ =0.6, 0.7 and 0.8). The results show that the velocity of the particles in all areas of the neck is about 2.8. 2.4. and 2.2 times more than the velocity of the particles in the channel direct section. Furthermore, the channel width has not so much effect on the increase velocity of the particles in the channel neck.

To study the effect of upper and lower walls on the velocity of the particles, it investigates in x-direction in channel center at different heights ($\frac{d}{H}$ =0.5, 0.6, 0.7, 0.8, 0.9 and 0.95) as shown in Fig. 11. The results show that as we close to the upper and lower walls, the velocity of the particles is decreased and the precipitation possibility of the particles increased.

The precipitation of the particles in the microchannel is one of the destructive phenomena and of disadvantages of liquid-solid two-phase flows in the microfluidics tools. This phenomenon is usually a function of material of the particles and channel, the density of container fluid and dispersed phase of flow geometry. Although in this research, it was tried that the density of the container fluid was equalized to the particles' density through the pycnometer technique in order to minimize the precipitation of the particles. Microscopic observations show that some of the particles still precipitate on the lower wall of the channel. The precipitation of the particles in the direct and convergent-divergent microchannel is compared as shown in Fig. 12. It can be observed the precipitation of the particles in the direct channel [15, 16] and convergent-divergent one occurs for the first 6 min and 3 min, respectively. Given the results, using convergent-divergent channel averagely leads to 45% reduction of the precipitation of the particles comparing to the direct one. The main reason of this issue is increase of the particles' velocity due to the lateral walls effects in the convergent section of the microchannel. In conclusion, one of the most important applications of convergent-divergent channels

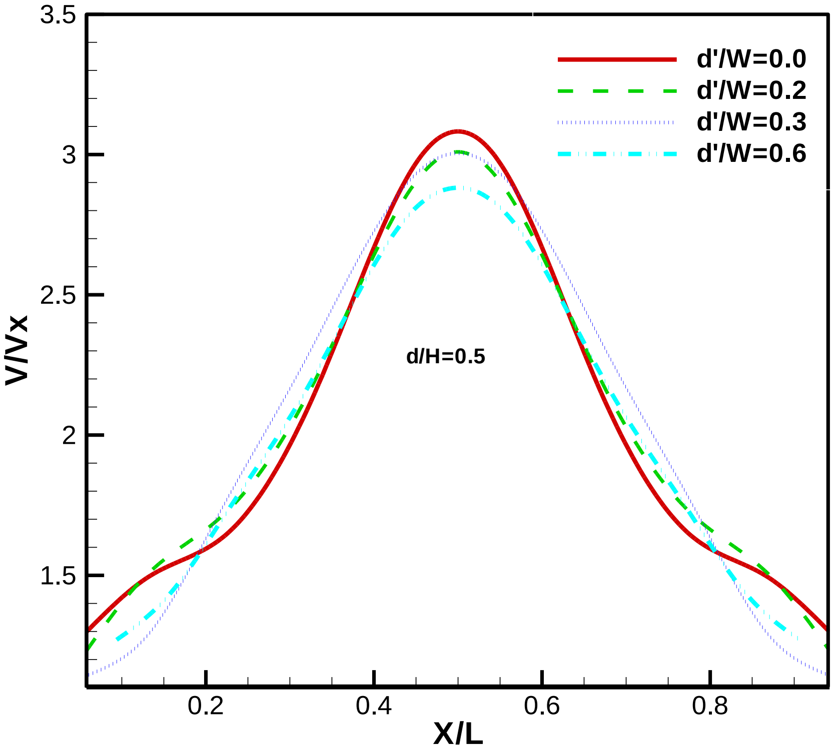

Figure 7: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.5$.

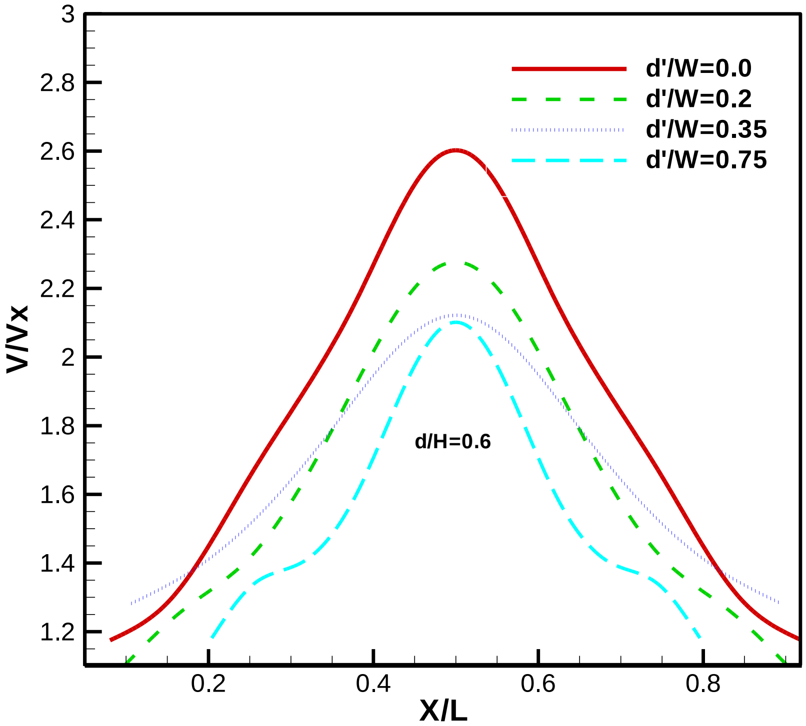

Figure 8: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.6$.

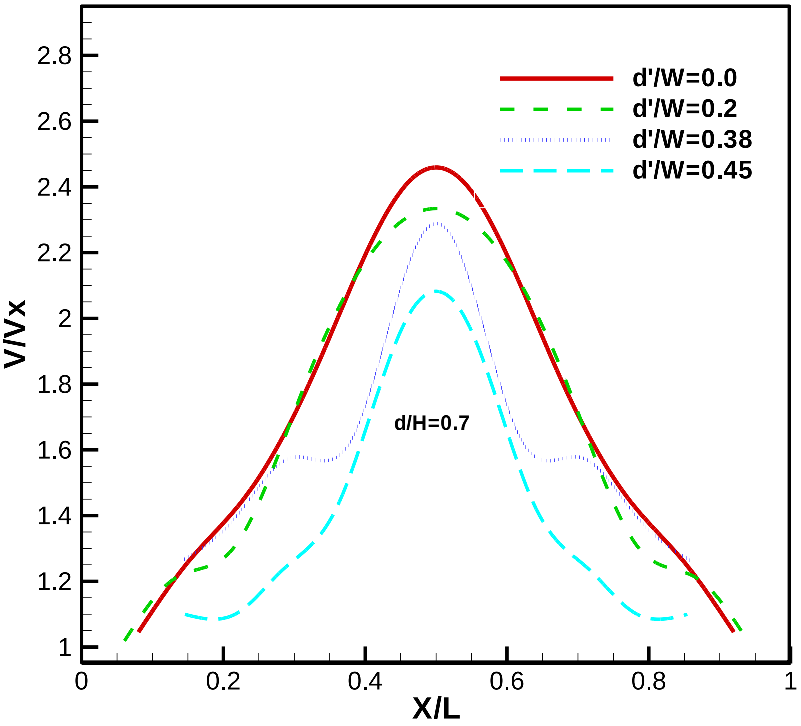

Figure 9: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.7$.

is prevention from destructive phenomenon of the particles precipitation in the micro channels.
The effect of Reynolds number on the precipitation decline is indicated in Fig. 13. The results show that the precipitation amount of the particles is decreased by increasing Reynolds number. Based on the results. the decline percentage of the precipitation in Reynolds number of 0.002, 0.005, 0.01, and 0.05 is equal to 10, 45, 85, and 73 in that order.
In this section, the portion of the shear stress and pressure gradient on the particles' velocity is investigated. The shear stress is calculated by Eq. (3.1),

$$\tau = \mu\frac{\partial U}{\partial Y} \tag{3.1}$$

where μ= 0.0015.
Besides the shear stress, the pressure gradient also affects the particles' velocity in different regions of the microchannel. The pressure ratio in the convergent section of channel was considered 3.18 [16]. Moreover. the pressure in the direct section of the channel is 35.3 μPa [15]. According the above results, the pressure was obtained 112.3 μPa in the different section of the channel.
To study the shear stress, at first, U velocity graph is plotted in Fig. 14 in terms of Y. The slope of aforementioned graph in different areas shows the velocity gradient which can be used to calculate the shear stress in different areas using Eq. (3.1).
The graph slope is equal to zero in the maximum point. Therefore, the shear stress amount is equal to zero in the middle of the microchannel. As can be seen in Fig. 15, the effect of shear stress on the velocity of the particles is more than the pressure gradient. This shows that the velocity of the particles in different areas is more under influence of the shear stress.
Figs. 16-21 depicts the closest particle to the wall at different heights. In the suspending flows, the particles become close to the wall, but they can never stick to the side wall. The factor of adhesion absence between the particles and walls in internal flows is the force that applies from the wall to

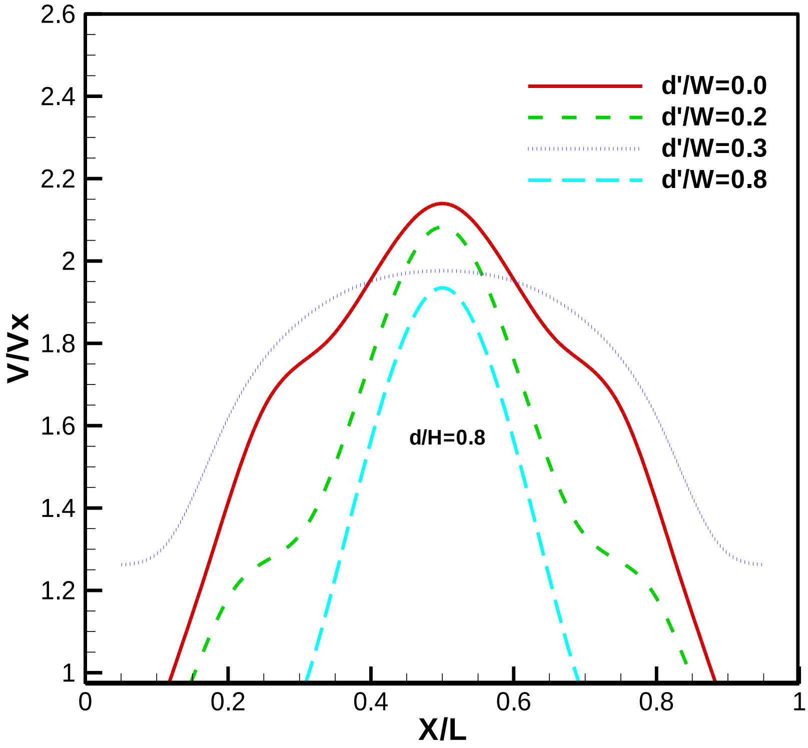

Figure 10: The velocity of the particles in y-direction in the convergent-divergent channel length in $\frac{d}{H} = 0.8$.

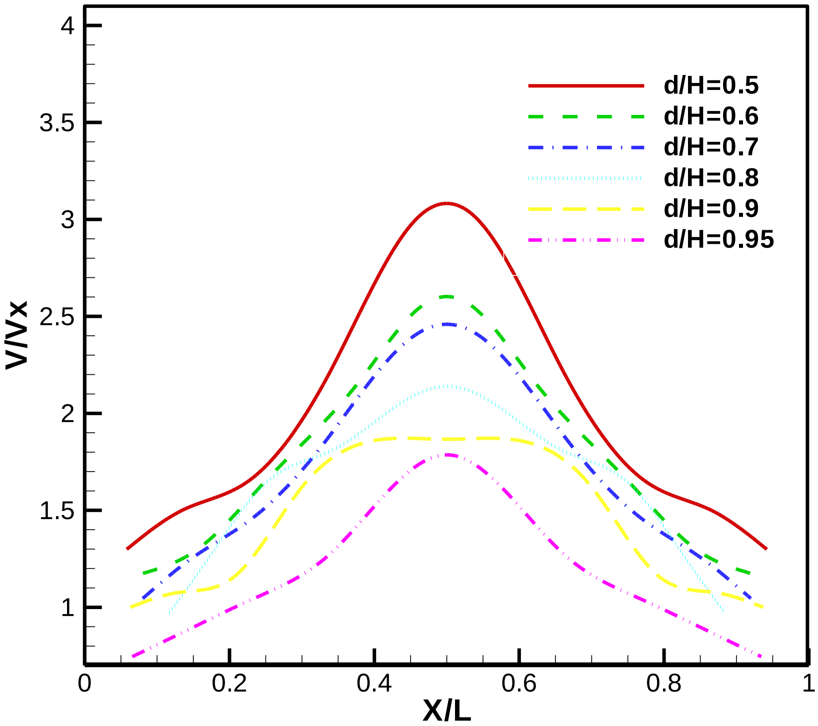

Figure 11: The velocity of the particles in x-direction in convergent-divergent channel at different heights.

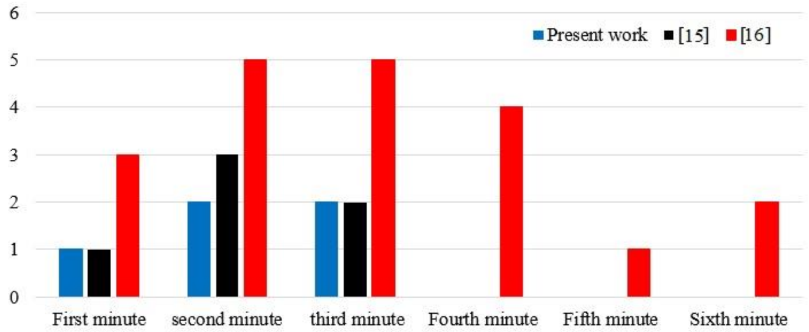

Figure 12: Particles precipitation graph in the direct and convergent-divergent micro channels.

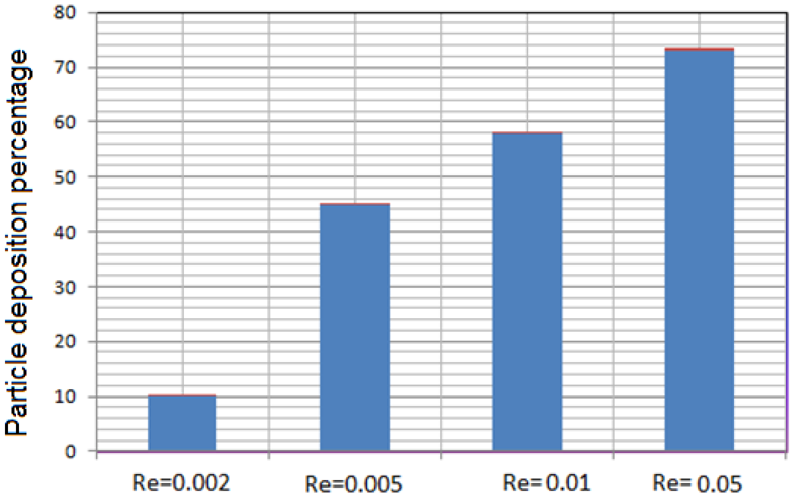

Figure 13: The effect of Reynolds number on the particles precipitation in the convergent-divergent microchannel.

the particle and from the particle to the wall. This is wall lubrication force. In this paper, using the Paint software, we obtain the distance from the channel wall (d') in pixels and multiply by 0.6, to convert it to the micrometer. As a final point, a column graph is plotted in terms of obtained numbers and height as shown in Fig. 22.

4. Conclusion

The goal of this research is to experimentally study the transfer of circular micronics particles into the convergent-divergent microchannel with low Reynolds number and effective factors on it. The water-glycerin suspension containing silicon particles was prepared and its creeping flow in a convergent-divergent microchannel was investigated using an optical microscope equipped to the xerography system. The results showed that the velocity of the particles in y-direction has a huge effect on the motion of the particles in the convergent-divergent channels. The study of particles precipitation in different Reynolds numbers showed that in the low Reynolds numbers, because of increase of the precipitation, the destructive effect of channel obstruction can be eliminated by means of a convergent-divergent channel. The shear stress and velocity gradient are two main factors of particles' velocity in the convergent-divergent channel. The result showed that the shear stress has more influence on the velocity of the particles than the velocity gradient. Moreover. besides the upper and lower walls. the side walls also affect the particles' velocity.

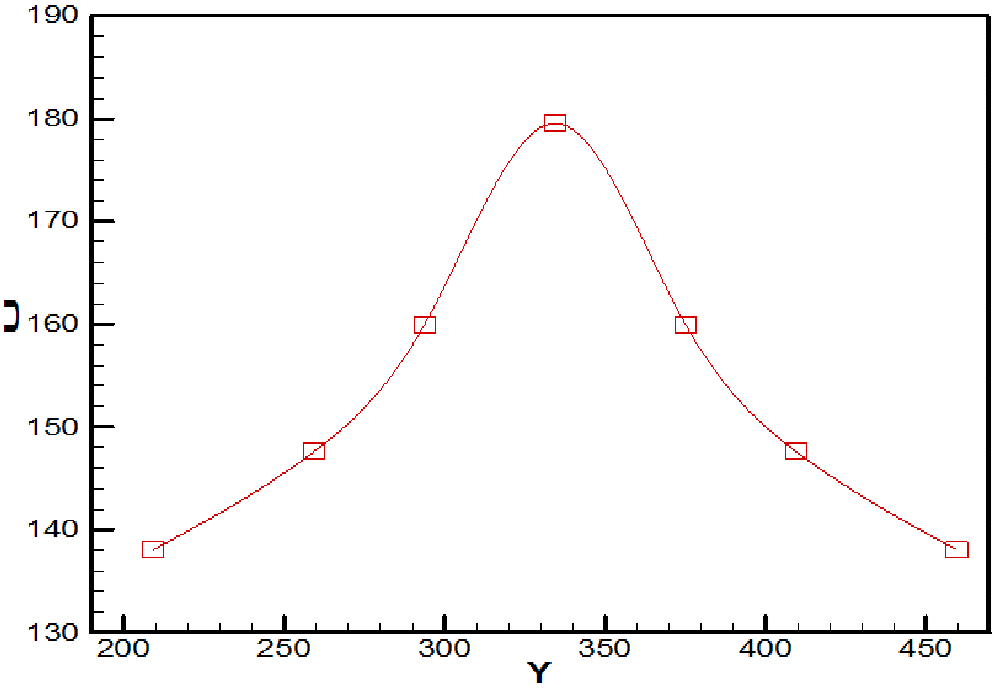

Figure 14: U velocity versus Y in height of $\frac{d}{h} = 0.5$.

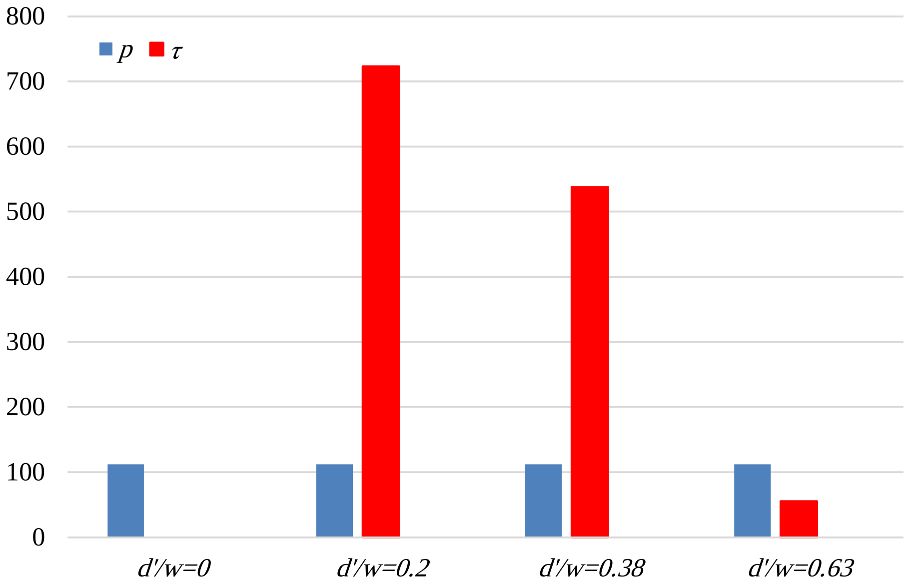

Figure 15: Pressure and stress graph in $\frac{d}{h} = 0.5$.

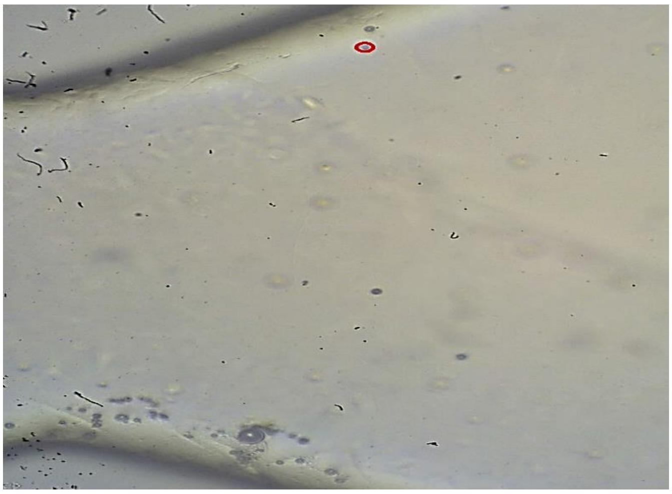

Figure 16: The closest particle to the wall at height of $\frac{d}{h} = 0.5$.

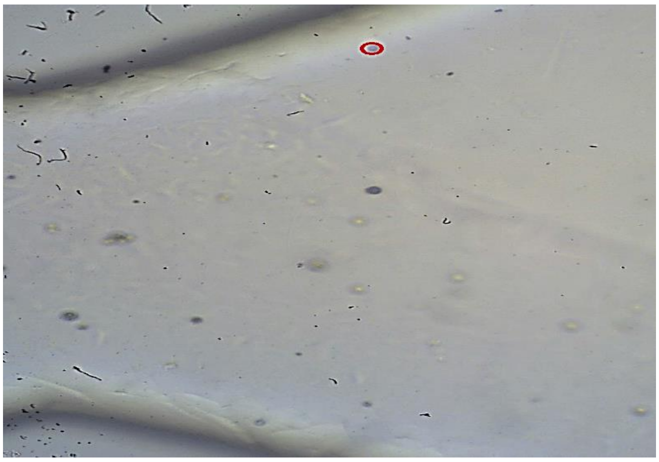

Figure 17: The closest particle to the wall at height of $\frac{d}{h} = 0.58$.

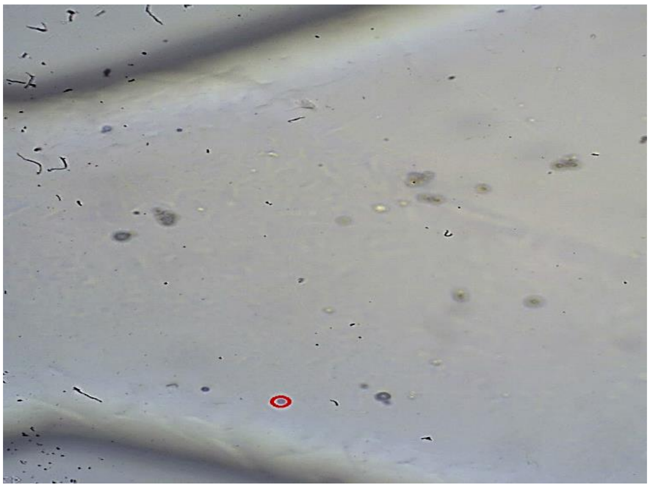

Figure 18: The closest particle to the wall at height of $\frac{d}{h} = 0.66$.

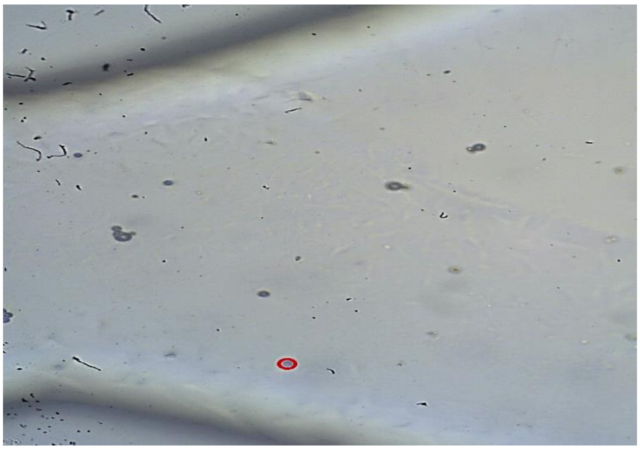

Figure 19: The closest particle to the wall at height of $\frac{d}{h} = 0.74$.

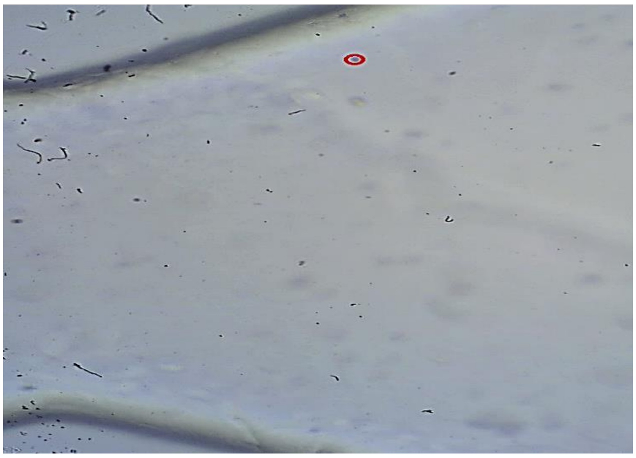

Figure 20: The closest particle to the wall at height of $\frac{d}{h} = 0.82$.

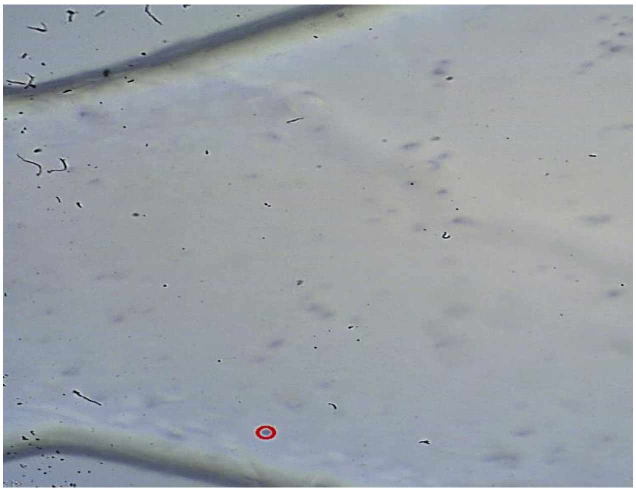

Figure 21: The closest particle to the wall at height of $\frac{d}{h} = 0.9$.

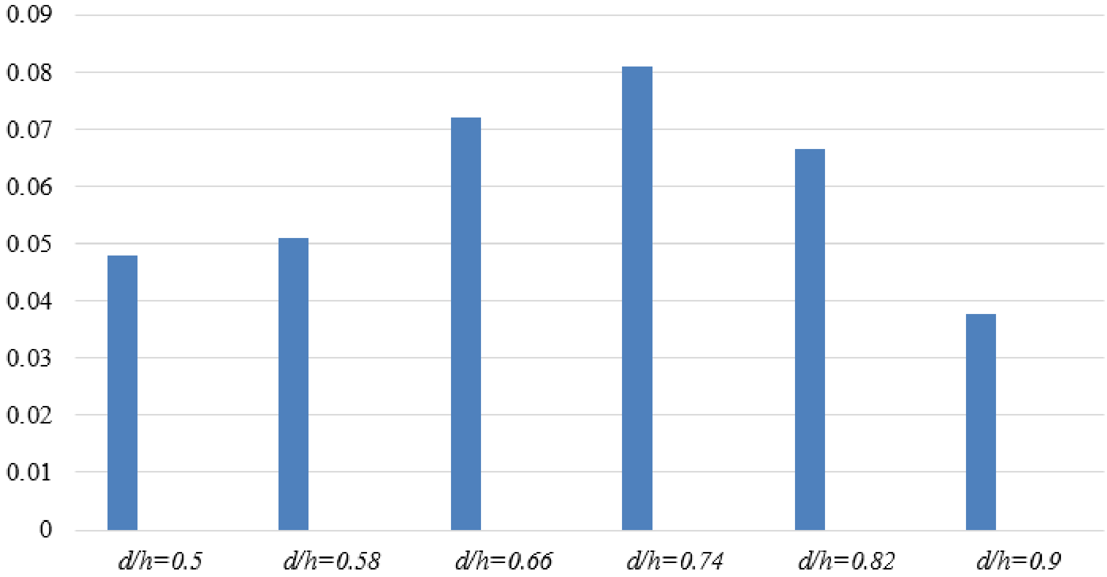

Figure 22: Particle distance graph from the wall at different heights.

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