Particle Behavior in a Non-Coaxial Sheath Flow

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Introduction

In this paper a study is presented on the behavior of particles in a sheath flow. In general a sheath flow in a micro-channel has many benefits [1], such as fewer problems with air-bubbles, a low detection limit and less critical fabrication tolerances. A series of experiments was designed to investigate whether it is feasible to have these benefits of a sheath flow also in micro-systems for the analysis of particles.

The studied sheath flow is to be applied in an integrated Coulter counter [2] with a liquid based aperture defined by a non-coaxial sheath flow [3]. The sheath flow consists of a non-conductive liquid that partially surrounds a flow of conductive liquid, which defines the Coulter aperture. The main advantage of this device is that the Coulter aperture can be optimized dynamically to the particle size.

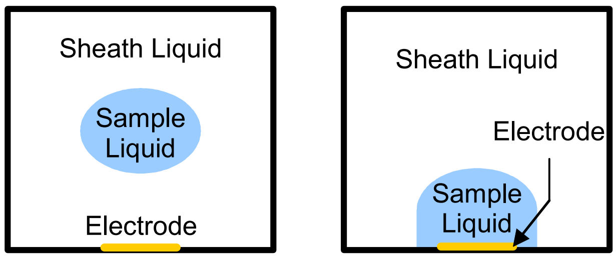


Fig. 1: In the traditional coaxial sheath flow, the sheath liquid completely surrounds the sample liquid (left); in the non-coaxial sheath-flow studied here the sample liquid still touches the channel wall.

Sheath Flow

A sheath flow can be defined as a combined flow profile in a channel that consists of two non-interacting liquids. One of these liquids is the sample liquid that is to be analyzed and the second liquid, the sheath liquid, has the function to control the position and to fix the dimensions of the flow of sample liquid. Micro-systems are very suitable to be used with a sheath flow because due to the small channel dimensions the Reynolds number is low and as a consequence the flow behavior is typically laminar.

The most common sheath flow is the coaxial sheath flow, where the sheath liquid completely surrounds the sample liquid in the channel cross-section (see Fig. 1 left). This particular flow-profile is most often combined with optical analysis systems. However, in our application an electrical contact with the sample liquid is required and therefore a non-coaxial flow profile will be used (see Fig. 1 right). In this flow profile the sample liquid still touches the channel wall which allows measuring the impedance of a certain section of the sample flow.

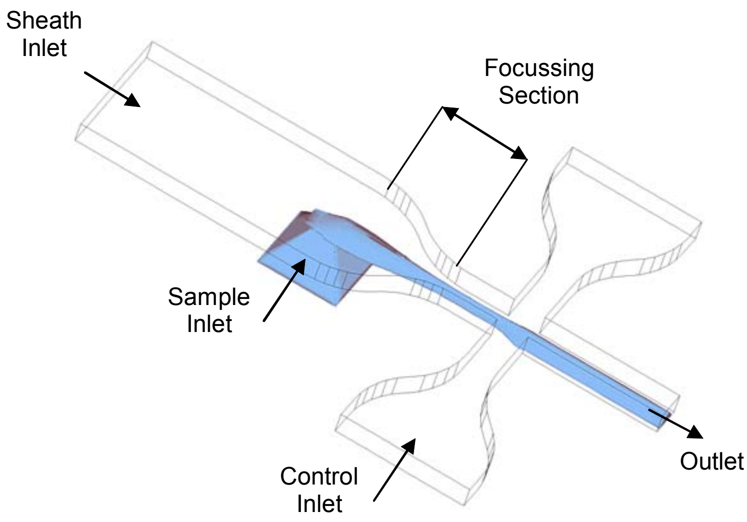


Fig. 2: The non-coaxial sheath flow is formed by injecting the sample liquid perpendicularly into a channel through which sheath-liquid is flowing.

The non-coaxial flow profile is obtained with a micro-machined flow-cell that is depicted in Fig. 2. The sheath-liquid flows through a micro-channel, and at a certain point, perpendicular to the direction of flow, the sample liquid is injected into the sheath liquid. Due to hydrodynamic focusing a narrow stream of sample liquid is formed that is partially surrounded by the sheath liquid. A focusing section down-stream of the sample inlet reduces the lateral dimensions of the sheath-flow to the right order of size. The two control inlets finally allow adapting the sample flow dimensions to the size of the particles to be analyzed [3].

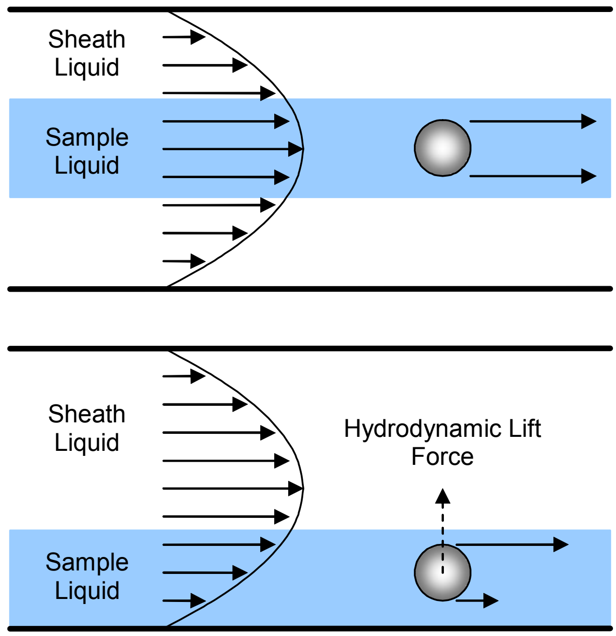


Fig. 3: In the coaxial sheath-flow the parabolic flow profile does not cause any net forces in the vertical plane (top); in the non-coaxial sheath flow the particle experiences a velocity gradient, which results in a hydrodynamic lift force (bottom).

Particle-Liquid Interaction in a Parabolic Flow Profile

The electrical particle size measurements with the Coulter counter are possible only when the particles remain in the core of conductive sample liquid, but this is not trivial. Since the integrated Coulter counter will use a pressure-driven flow to move the liquids through the device the velocity profile in the channel will be parabolic. In the case of the axis-symmetric flow-profile of the classical coaxial-sheath flow the particle will still undergo a symmetrical velocity gradient that does not give rise to any net force pushing the particles out of the centre of the flow.

However, for the non-coaxial sheath flow analyzed here the situation is quite different. The particles are located in the sample liquid at the bottom of the channel and will therefore experience a non-symmetrical velocity gradient (see Fig. 3) that will result in hydrodynamic lift forces that tend to push the particle in the direction of the highest flow velocity. The dominant effect is the Bernoulli effect: the pressure in a fluid decreases as the speed of the fluid increases. Since the speed over the particle is higher than the speed underneath the particle, the particle will experience an upward force.

Experiments

Due to the planar nature of the device (see Fig. 4) it is only possible to study the particle behavior from the top view, so only its behavior in the horizontal plane can be observed. To overcome this problem a series of controlled experiments was designed that not only allows to draw conclusions about particle behavior in the horizontal plane, but also permits conclusions about their behavior in the vertical plane from observations in the horizontal plane.

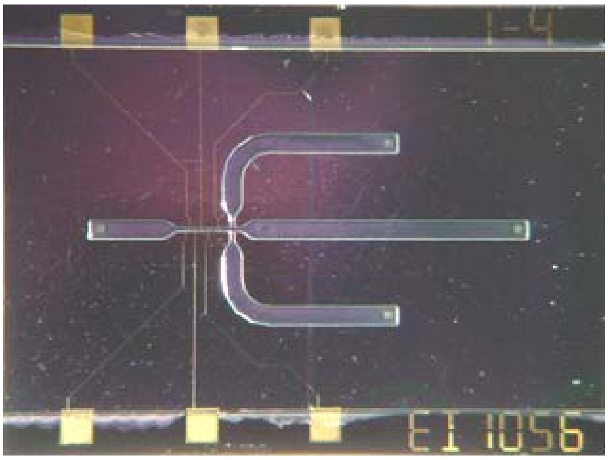
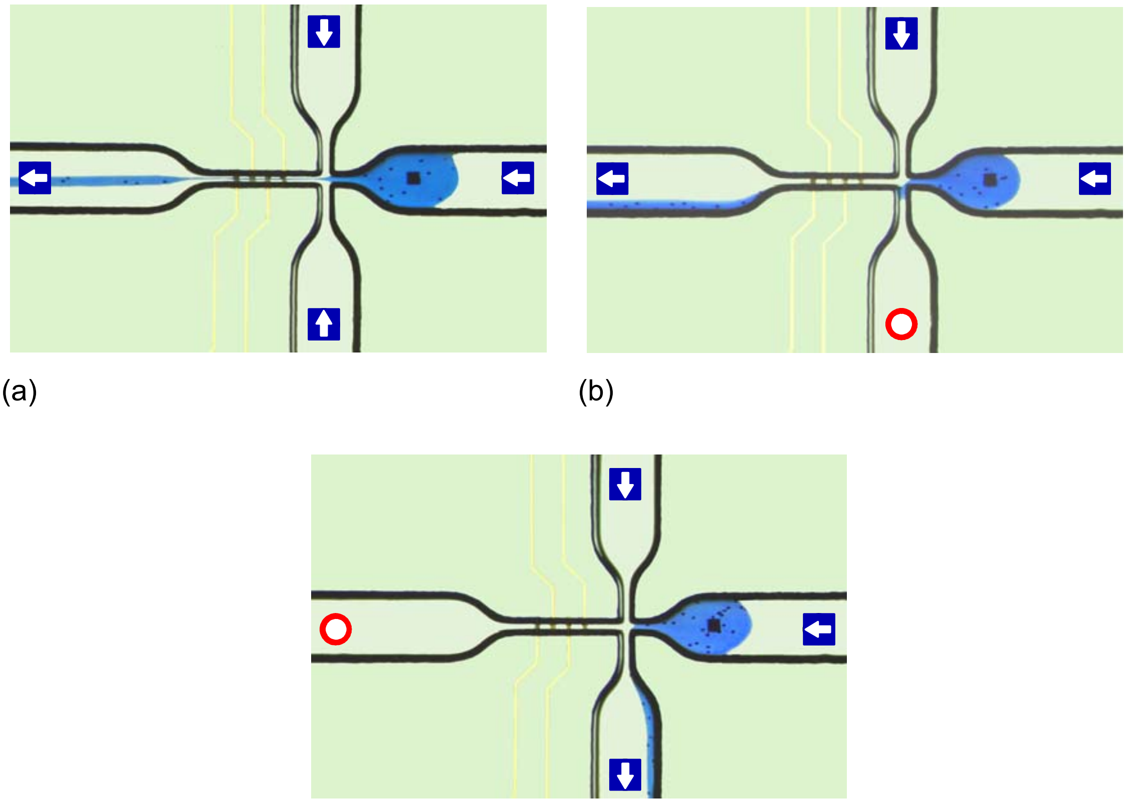


Fig. 4: Photograph of the sheath flow chip.

In the first experiment the flow-cell is used under normal operation conditions. The sample liquid is focused in the aforementioned non-coaxial sheath flow in the middle of the channel in the horizontal plane (see Fig. 5 (a)). It can be seen the particles do not leave the sample liquid, which was to be expected, since the particles do not experience a gradient in the velocity in the horizontal plane. From this experiment it can also be seen that a stable and smooth sheath flow is formed.

In the second experiment the control inlets that are normally used to control the width of the sample flow are now used to focus the sample liquid to one side of the device. The particles experience a steep velocity gradient in the horizontal plane and as a consequence they are exposed to a hydrodynamic force towards the middle of the channel. But from Fig. 5 (b) it becomes clear that in the horizontal plane the particles remain within the sample flow. From these results it can be concluded that under normal operation the particles (with a density equal to or higher than the density of the liquid) will not leave the sheath flow in the vertical plane, since the conditions are comparable in the vertical plane, and additionally the particles will also be pulled down by gravitation.



(a) (b) (c)

Fig. 5: Photographic results of the experiments; the sample liquid is successively focused in the center (a), to one side (b) and forced to make a steep turn (c).

From the previous two experiments it can be concluded that once the particles are located in the sample flow they will not leave it. To investigate whether the particles will stay in the sample flow just after the injection into the flow channel a third experiment was carried out. Now the sample flow with the particles is focused to one side and forced to make a steep turn. This experiment mimics the situation at the sample inlet, where the particles enter the flow channel from the bottom and are forced to make a steep 90 degree turn. If the particles would not be able to make such a steep turn at the sample inlet, they might end up in the sheath liquid as a consequence of centrifugal forces. This situation has been transformed into the horizontal plane with this experiment. In Fig. 5 (c) it can be seen that again the particles do not leave the sample liquid. This means that apparently the centrifugal forces are not dominant.

Conclusions

From the experiments it can be concluded that laminar flow conditions are present in the flow channel and that a stable sheath flow is formed. Once particles are in the sample liquid of the sheath flow they will remain there despite hydrodynamic lift forces that push the particle in the direction of the highest liquid velocity. Steep corners will also not cause the particles to leave the sample liquid despite centrifugal forces. So, in summary, the particle behavior in the sheath flow studied here is such that the particles will always remain in the sample liquid which makes the sheath flow suitable for application in an integrated Coulter counter or other particle analysis instruments.

References

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[2] W.H. Coulter, Means for counting particles suspend in a fluid, US patent no. 2,656,508, October 20, 1953

[3] J.H. Nieuwenhuis, J. Bastemeijer, P.M. Sarro, M.J. Vellekoop, Integrated Coulter Counter with Non-Coaxial Sheath-Flow and Dynamic Aperture Control, Proc. of Eurosensors 2002, September 15-18, Prague, Czech Republic, p1194-1197