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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1039/C0LC00723D>

Lab on a Chip, 11, 10, pp. 1717-1720, 2011-04-11

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Cite this: *Lab Chip*, 2011, **11**, 1717

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COMMUNICATION

Air stream-mediated vortex agitation of microlitre entities on a fluidic chip

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Received 24th December 2010, Accepted 24th March 2011

DOI: 10.1039/c0lc00723d

The method presented in this paper uses air flux to induce spiral motion in small-scale (*e.g.*, microlitre) fluid entities in an efficient, technologically convenient manner. The set-up entails a manifold that modulates the air flux and projects it onto a liquid-containing reservoir. The flow behaviour of the liquid phase has been visualized through the dissolution of rhodamine B crystallites and the motion of fluorescent microbeads. In addition, the method proved effective to restoring a suspension of spherical particles upon sedimentation, promoting displacement and capture of the beads within a micro-fluidic system.

Vortex flow results from turbulent, spiral motion in liquid or gaseous environments, and is immanent to a broad range of natural and technological processes, many of which occur on macro- and mesoscopic scales.¹ For miniaturized systems, on the other hand, vortex flow is not a common feature. When confined to boundaries with reduced dimensions, low Reynolds numbers dominate the flow regime, resulting in laminar (non-turbulent) motion of fluids.² For laminar flow conditions often represent a shortcoming to the integration of chemical or biological processes, a number of approaches have been developed in recent years to induce convection for mixing reagents beyond the limitations of molecular diffusion.^{2–11} Spiral motion of fluids in microfluidic systems can be promoted, for example, by implementing topographic, flow-diverging elements in the trajectory.^{3–5} An alternative concept involves displacement, separation, or merging of droplets which leads to circulation and reflow effects within discrete fluid entities.^{6,7} Small-scale vortices can further be induced through the rotational movement of miniaturized spinning elements.^{8,9} Herein, we exploit a circulating flux of compressed air which transmits momentum and kinetic energy to the fluid phase.

The experimental set-up used within this study comprises two principal components—a manifold and a cartridge—whose arrangement and configuration are depicted in Fig. 1. The manifold is composed of a socket and a lid which were custom-fabricated from a transparent polymer resin using laser-induced photopolymerization (Axis Prototypes, Saint-Léonard, QC). The socket serves as a rigid support enabling convenient assembly of the cartridge and the manifold (Fig. 1A). The structure is adapted for self-alignment and

provides a ball lock mounting system that holds the manifold lid in place during operation. Each lock unit is oriented horizontally to exert force from opposite directions upon the lid. Designated cavities

Fig. 1 Experimental set-up for vortex agitation of confined fluid entities. (A) Photograph of the setting as it was used within this study (see text for details). (B) Cross-sectional view (left-hand panel) and top view (right-hand panel) detailing the internal configuration of both manifold lid and cartridge: (1) supply channel; (2) chamber with cylinder-like geometry; (3) exit channel; (4) fitting for screw valve; (5) O-ring; and (6) liquid-containing reservoir.

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at the side-wall of the lid provide the counterparts that can intersect with the portion of the ball that is extending from the sleeve. While contact between the two is firm, the lid can be removed conveniently for the ball can rotate and move backward upon lifting. A holder at the back end of the socket makes it possible for the manifold to be mounted on a stage. The bottom of the socket has been spared to some extent to enable observation of flow behaviour within the cartridge by using a confocal microscope. The manifold lid functions as a modular interface¹² that mediates the supply of compressed air from a custom-built pressure control unit to the designated reservoirs on the cartridge. The design of both manifold and cartridge allows for agitating eight reservoirs independently and in parallel. The central part of the internal pathway (Fig. 1B) is a chamber with cylinder-like geometry destined to induce turbulence while projecting air flux against the fluid. The air stream is forced into circular motion as the supply channel enters the chamber in a tangential fashion—an operational principle that is equally used for generating large-scale cyclones in sorting and separation systems. The chamber is sealed by an O-ring upon contact with the cartridge. The exit is equipped with a screw valve destined to adjust the flux passing through the conduit. For testing purposes, we conceived a relatively simple cartridge design based on transparent, thermoplastic polymers which are arranged in the form of a three-layer stack with rectangular geometry (measuring 72 mm in width and 112 mm in length). Top and bottom layers (1 mm in thickness, respectively) are both made of hard plastic materials (*e.g.*, Zeonor® 1060R; Zeon Chemicals, Louisville, KY) while the centre part (2 mm in thickness) consists of an elastomer sheet (*e.g.*, Versaflex® CL30; GLS Corp., McHenry, IL)^{13,14} serving as a double-sided adhesive that holds the stack together. Reservoirs were implemented as circular openings (*e.g.*, 4.5 mm in diameter) by punching the elastomer sheet prior to assembly. The hard plastic top layer comprises through-holes (*e.g.*, 2.5 mm in diameter) which are aligned with the respective punch marks in the elastomer sheet during the assembly of the chip.

We performed a series of experiments to validate the functioning of the set-up and test the efficiency of agitation and mixing. In a first demonstration, we added crystallites of rhodamine B (Fluka, Buchs, Switzerland) to a water reservoir and monitored the distribution of the dye as a function of time (Fig. 2). Within the first few moments of mixing, the formation of vortex lines is readily apparent in the flow pattern while the dissolving fluorophore is dragged away from its initial location (Fig. 2A). As agitation continues, the vortex lines disappear while the dye is distributed uniformly within the liquid reservoir. The fluorescence intensity increases with time as long as the crystallites continue to dissolve. Although it is unlikely that dissolution of rhodamine B has reached completion, the signal readily flattens as shown by the graph in Fig. 2B. This finding is indicative of a well-mixed, homogeneous solution that has been formed within a very short period of time (*e.g.*, <10 s). The effect of vortex-mediated mixing is contrasted by the result of a control experiment (Fig. 2C) in which we followed the dissolution of rhodamine B crystallites without agitation of the reservoir. Here, the fluorescence intensity continues to rise over a period of at least 10 min (which represents the limit of observation in this series), suggesting that diffusion phenomena alone (considering a diffusion coefficient of $D = 4.2 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$)¹⁵ remain insufficient to equilibrate the solution within this time frame.

In a second trial, we used a suspension of microbeads, making it possible to display flow characteristics in a continuous fashion. The particles follow the spiral motion of the liquid in the reservoir as

Fig. 2 Effect of vortex agitation on the dissolution of rhodamine B crystallites. (A) Sequence of fluorescence micrographs taken with an Eclipse TE2000-U inverted microscope (Nikon, Melville, NY) equipped with an EM-CCD camera (Hamamatsu, Bridgewater, NJ) revealing the distribution of the dye in 40 μL of water during the initial phase of agitation. (B) Plot of the fluorescence intensity as a function of agitation time quantifying the trend that is depicted in (A). (C) Evolution of the fluorescence intensity during dissolution of crystallites without agitation.

revealed by the images in Fig. 3. Rotation in both clock-wise and counter-clock-wise directions is possible depending on the internal configuration of the manifold lid. The air flux had a direct impact on the velocity of the particles, and was regulated by changing the pressure of the gas supply and the position of the screw valve. We commonly performed experiments at a pressure range of 4–12 psi while maintaining the flux at a relatively low level so that the displacement of individual particles in the fluid phase can be tracked using a standard CCD camera. It is straightforward, however, to raise the air flux passing through the system and attain higher particle velocities whenever necessary (data not shown). Closing of the screw valve interrupts the air flux in the system and halts the motion of the fluid phase. The process is fully reversible, and vortex flow can be reactivated instantaneously, provided that the system remains pressurized.

In a final example, we used vortex agitation to counterbalance the effect of precipitation in a suspension of spherical particles and enable their displacement within a microfluidic system (Fig. 4). The cartridge used for these experiments entails a set of fluidic channels that emerge

Fig. 3 Fluorescence images of Cy3-labelled microparticles during agitation. The flow can be directed in a clock-wise (left-hand panels) or counter-clock-wise (right-hand panels) fashion depending on the orientation of the incoming air supply channel. The beads encircled in cyan and red indicate the flow direction. Note that the flow regime gradually changes from the bottom to the top of the suspension as can be observed through variation of the focal plane within the three-dimensional vortex system. The sample volume injected on the cartridge was 40 μL in both cases. Carboxylated polystyrene beads (5.01 μm in diameter; Bangs Laboratories, Fishers, IN) were functionalized by incubating 10 μL of the suspension (10.4% solid content) with 1 mg *N*-hydroxysuccinimide (Sigma-Aldrich, Oakville, ON), 4 mg 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (Sigma-Aldrich), and 50 μL solution (128 μM) of a Cy3-labelled 27mer (modified with a primary amino group in the 3' position; Integrated DNA Technologies, Coralville, IA) in phosphate buffered saline (pH = 7.4, Sigma-Aldrich) in a plastic tube (Eppendorf Canada, Mississauga, ON) at room temperature for ~ 2 h. The sample was washed several times with de-ionized water before experimental use. The scale bar denotes 500 μm .

from a circular entry port and lead to a constriction zone acting as a barrier for particles that move along the trajectory (Fig. 4A).^{14,16,17} The vertical dimensions of the constriction have been adjusted for the capture of polystyrene beads that are 22.7 μm in diameter, promoting lateral accumulation into a dense, well-defined monolayer.^{14,18} Liquid passing through the constriction is accumulated in a designated reservoir at the end of the trajectory (not shown). The fluidic system was realized by hot embossing using an EVG 520 embossing tool (EV

Fig. 4 Application of vortex flow to the capture of microbeads in a microfluidic system. (A) Sketch (top view) of the trajectory comprising a macroscopic inlet and a constriction zone. The channel is about 10 cm long and has been segmented for representation purposes. Support structures are included in the channel entry region and the weir to increase the fill factor of these low-aspect-ratio features. The colour coding of the constriction zone in the close-up view indicates a channel depth of 26.2 μm (orange) and 12.4 μm (yellow), respectively. (B) Schematic illustration (cross-sectional view) of the inlet area containing a suspension of microbeads. The particle suspension is pushed towards the constriction zone using compressed air provided by the manifold. (C and D) Optical microscope images of inlet sections (left-hand panels) and constriction areas (right-hand panels) revealing the capture efficiency for streptavidin-coated polystyrene particles (22.7 μm in diameter; Sphero-tech, Lake Forest, IL) with and without vortex agitation. In both cases, 40 μL of an aqueous suspension whose concentration has been adjusted to 10 beads μL^{-1} was injected in the entry port of the cartridge. Beads were allowed to settle over a period of 5 min. (C) Short agitation (e.g., for 1 min) restored the suspension and a large number of particles (e.g., 321) accumulated in the capture zone. Only a small portion of the beads was present in the inlet. The control experiment in (D) reveals quite the opposite: few particles (e.g., 43) have reached the constriction area, while the majority remained immobilized at the bottom of the inlet. In both examples, a pressure of 8 psi was applied to the inlet for a period of 1 min, dispensing $\sim 80\%$ of the injected sample volume. Scale bars correspond to 100 μm .

Group, Schärding, Austria; operated at 135 $^{\circ}\text{C}$ with an applied force of 1.5×10^3 N) and a silicon mold that was prepared by photolithography in conjunction with SU-8 resist.¹³ Openings are punched in a manual fashion. Assembly of the three-layer stack results in a circuit of embedded microchannels at the inner bottom side of the cartridge (Fig. 4B). The relatively large particles readily precipitate from the suspension and accumulate at the bottom of the inlet within moments after injection. Vortex agitation proved effective to lift these particles off the bottom and restore the original suspension. Interestingly, the fluid remains confined to the entry port during agitation (e.g., 1 min at 8 psi), entering the channel only when closing the screw valve to interrupt the air flux within the manifold. The pressure gain thereby helps overcome the channel's resistance to flow. Fig. 4C illustrates the outcome of a capture experiment involving ~ 400 beads. The yield of beads accumulating at the constriction is 80%, which correlates well with the overall volume that has been displaced in this example. The

In summary, we have investigated the use of circulating air flux as a means of inducing vortex flow in fluid entities on a chip. The key element is a relatively simple conduit provided by the manifold lid along with few, unsophisticated pressure regulation units. Proof-of-concept demonstrations suggest that air stream-mediated vortex agitation can readily promote a number of on-chip operations that may involve (i) mixing of multiple components, (ii) restoration and distribution of particle suspensions, or (iii) equilibration of temperature, among others. Tuning of the air flux allows for controlling flow behaviour in the liquid phase, yet a more detailed assessment of the interplay between the two remains to be achieved. The design of both manifold and cartridge is flexible and can be adjusted to a variety of formats, potentially promoting integration at higher levels of complexity. While a sample volume of 40 μL proved convenient for the work presented in this paper, we believe that the system can accommodate both larger and smaller volumes ranging from the millilitre to the lower microlitre scale without major alterations in the design. It can be expected, however, that evaporation of liquid becomes an issue for low-volume reservoirs that may set a practical limitation in downscaling the dimensions of the fluidic units on the chip.

This work was supported in part by Defence Research and Development Canada, Centre for Security Science, Chemical, Biological, Radiological/Nuclear, and Explosives Research and Technology

References

- 1 H. J. Lugt, *Vortex Flow in Nature and Technology*, John Wiley & Sons, New York, 1983.
- 2 T. M. Squires and S. R. Quake, *Rev. Mod. Phys.*, 2005, **77**, 977.
- 3 A. D. Stroock, S. K. W. Dertinger, A. Ajdari, I. Mezić, H. A. Stone and G. M. Whitesides, *Science*, 2002, **295**, 647.
- 4 J. P. Shelby, D. S. W. Lim, J. S. Kuo and D. T. Chiu, *Nature*, 2003, **425**, 38.
- 5 A. P. Sudarsan and V. M. Ugaz, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 7228.
- 6 P. Paik, V. K. Pamula and R. B. Fair, *Lab Chip*, 2003, **3**, 253.
- 7 M. R. Bringer, C. J. Gerdtts, H. Song, J. D. Tice and R. F. Ismagilov, *Philos. Trans. R. Soc. London, Ser. A*, 2004, **362**, 1087.
- 8 B. A. Grzybowski and G. M. Whitesides, *Science*, 2002, **296**, 718.
- 9 C. J. Campbell and B. A. Grzybowski, *Philos. Trans. R. Soc. London, Ser. A*, 2004, **362**, 1069.
- 10 N.-T. Nguyen and Z. Wu, *J. Micromech. Microeng.*, 2005, **15**, R1.
- 11 V. Hessel, H. Löwe and F. Schönfeld, *Chem. Eng. Sci.*, 2005, **60**, 2479.
- 12 C. K. Fredrickson and Z. H. Fan, *Lab Chip*, 2004, **4**, 526.
- 13 M. Geissler, E. Roy, G. A. Diaz-Quijada, J.-C. Galas and T. Veres, *ACS Appl. Mater. Interfaces*, 2009, **1**, 1387.
- 14 J.-F. Gravel, M. Geissler, S. Chapdelaine, B. Voisin, K. Boissinot, I. Charlebois, H.-P. Poirier-Richard, A. Grégoire, M. Boissinot, M. G. Bergeron, T. Veres and D. Boudreau, in preparation.
- 15 P.-O. Gendron, F. Avaltroni and K. J. Wilkinson, *J. Fluoresc.*, 2008, **18**, 1093.
- 16 M. Grumann, M. Dobmeier, P. Schippers, T. Brenner, C. Kuhn, M. Fritsche, R. Zengerle and J. Dürée, *Lab Chip*, 2004, **4**, 209.
- 17 J. Kim, J. Heo and R. M. Crooks, *Langmuir*, 2006, **22**, 10130.
- 18 E. Kumacheva, P. Garstecki, H. Wu and G. M. Whitesides, *Phys. Rev. Lett.*, 2003, **91**, 128301.
- 19 E. Verpoorte, *Lab Chip*, 2003, **3**, 60N.