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Centrifugo-magnetic pump for gas-to-liquid sampling

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Abstract

This paper describes a novel gas micropump realized on a centrifugal microfluidic platform. The pump is integrated on a passive and microstructured polymer disk which is sealed by an elastomer lid featuring paramagnetic inlays. The rotational motion of this hybrid over a stationary magnet induces a designated sequence of volume displacements of the elastic lid, leading to a net transport of gas. The pumping pressure was determined as a function of the frequency of rotation, with a maximum observable pressure of 4.1 kPa without further optimization.

The first application of this rotary device is the production of gas–liquid flows by pumping ambient air into a continuous centrifugal flow of liquid. The injected gas volume segments the liquid stream into a series of liquid compartments. Apart from such multi-phase flows, the new pumping technique supplements a generic air-to-liquid sampling method to centrifugal microfluidic platforms.

Keywords: Centrifugal microfluidics; Micropump; Segmented flow; Gas–liquid sampling

1. Introduction

The toolbox of centrifugal microfluidics has been continuously extended over the last decade. Up to now, a diverse set of unit operations such as cell-lysis [1], continuous micromixing [2–4], hematocrit determination [5] as well as applications in (bio-)analytics [6,7] and emulsification [8] for micro process engineering have been successfully implemented. However, the processing of gases in rotating microchannels still remains a challenge since the centrifugal field used for pumping scales with the fluid density, thus reducing the force density on gases by three orders of magnitude with respect to liquids. In particular the generation of gas–liquid flows is aggravated by the buoyancy of the gas under the strong "artificial-gravity" conditions of the centrifugal field.

To access the interesting field of gas–liquid flows [9] with our centrifugal platform, the gas has to be additionally pressurized with respect to the liquid. To comply with the modular concept of the rotary system, the typically disposable disk should remain passive and the force transmission ought to be accomplished in a contact-free fashion. We chose a centrifugo-magnetical principle to displace movable, disk-based steel plates which are incorporated in the lid by permanent magnets aligned along the orbit of the pumping chamber [10].

Several magnetically driven micropumps were presented recently where external electro-magnets deflect permanent magnets integrated on elastic membranes [11–13]. Silicone elastomers, predominantly PDMS, are commonly used due to their simple handling, adjustable elastic properties as well as their cost-efficiency [14,15]. Compared to these approaches, our novel design significantly simplifies the setup by drawing the power for both, the centrifugal liquid pumping as well as the pressurization of the gas, quasi-independently from the same rotary power source. Therefore, no additional power supply is needed to operate the gas-processing part.

The so realized centrifugo-magnetic pumping of gases supplements our recently presented centrifugal platform for continuous liquid-processing [2,8,16]. On this platform, liquid flows are propelled by the pulse-free centrifugal "artificial-gravity" field which is self-stabilized by the inertia associated with the spinning motion. The constant pumping force is of particular benefit for the well-controlled formation of liquid–fluid

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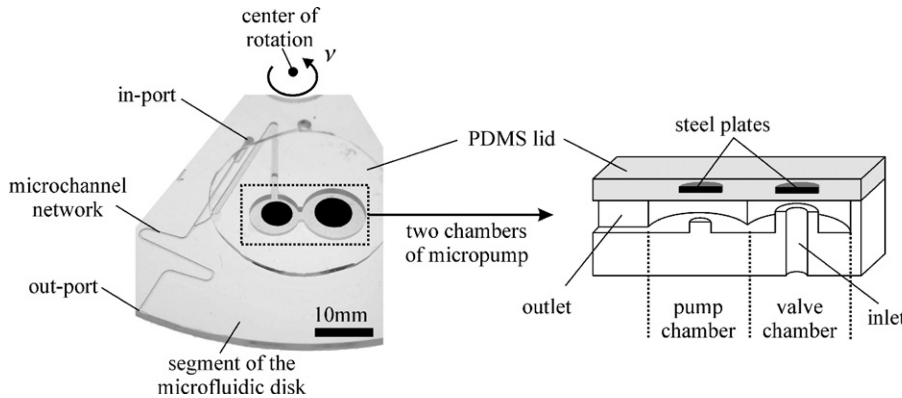

Fig. 1. Sector of the microfluidic disk featuring a network of sealed microchannels. A thin PDMS lid with a thickness of roughly 0.7 mm incorporating two steel plates is placed above the two pump chambers. The disk spins at a frequency ν to pump liquid through the microchannel network (starting from the in-port towards the out-port). In addition, environmental gas is pumped by the sequential displacement of the membrane into the pump chambers while passing a stationary permanent magnet (Fig. 2).

interfaces, e.g. water-in-oil flows, with respect to the reciprocating actuation principles of common mechanical pumps.

This paper starts with an outline of the principle of the centrifugo-magnetic gas pump followed by the device fabrication. Next, we supply the proof of concept and the experimental characterization of the pump. In the last section, the production of gas–liquid flows is presented.

2. Functional principle

Two chambers of our novel, centrifugo-magnetically actuated micropump are located at the same radial but different azimuthal positions. The two chambers are a valve chamber able to seal the gas inlet channel and a pump chamber compressing the gas inside the chamber and the connected channel network at the outlet. The two chambers are sealed by a flexible PDMS lid incorporating metallic inlays (steel, thickness: 400 μm, diameter: 5 mm for the pump and 6 mm for the valve chamber, respectively). The outlet of the pump is linked to a microfluidic channel network (Fig. 1).

The steel plate inlays above the chambers pass a conventional permanent magnet placed at a fixed position along the orbit of the pump. Its vertical distance is set to approximately 4 mm below the metallic inlays. The magnetic force triggers two phase-shifted displacements in the chambers (Fig. 2).

The pumping sequence exhibits four stages: (a) closing of the valve with the PDMS-membrane at the seat of the valve chamber; (b) compression of the pump chamber to displace a defined gas volume into the connected microchannel via the outlet while the valve is closed; (c) after the permanent magnet has passed the valve chamber, the inlet is opened again; in the last stage (d), the pump chamber is refilled by ambient gas due to the relaxation of the membrane (the magnet has now also passed the pump chamber). During the final step, the small hydrodynamic resistance of the refilling path (via the pump inlet) compared to the connection channel (connecting the pump outlet to the microchannel

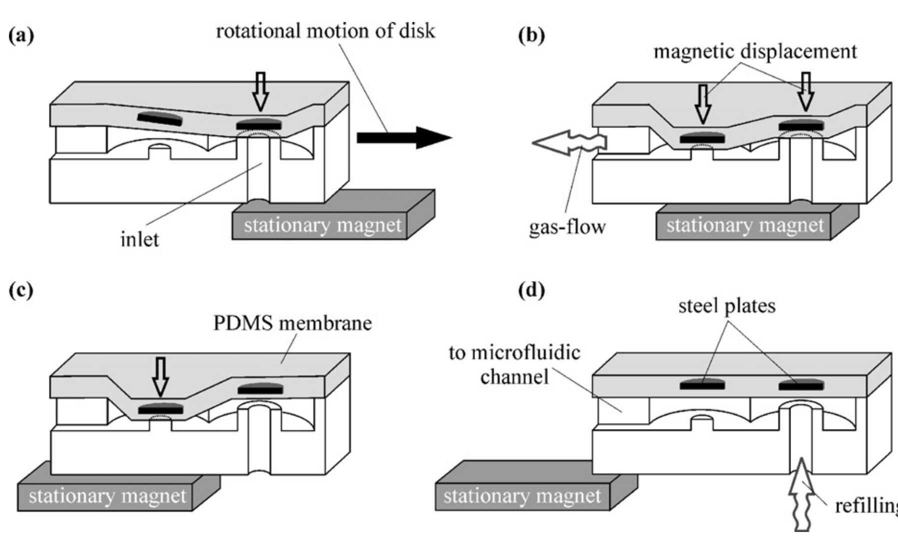

Fig. 2. Functional principle of the gas micropump. The pump chamber orbits above a stationarily mounted permanent magnet. The two steel plates within the PDMS lid are spaced at a defined azimuthal distance to induce a sequence of displacements during rotation for pressurizing the gas. After the magnet has passed, the chambers are primarily replenished by ambient gas through the inlet of the valve chamber.