

# A fast-response microfluidic gas concentrating device for environmental sensing

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## Abstract

This paper describes the design, fabrication and characterization of a microfluidic gas centrifuge for separating dilute gas mixtures based on the molecular weights of their constituents. The principal advantage of this approach is its fast response time compared to other methods that are based on permeation or adsorption/desorption. This would allow it to serve as a real-time preconcentrator for improving the sensitivity of miniature chemical sensors. Devices with nozzle throat widths as small as 3.6  $\mu\text{m}$  have been fabricated using photolithography, deep reactive ion etching (DRIE) and silicon-glass anodic bonding. Measurements of the device's performance show that a single stage can achieve a two-fold enrichment of an initially 1% mixture of  $\text{SF}_6$  in  $\text{N}_2$  in 0.01 ms. These experimental findings are consistent with the results of two-dimensional numerical simulations of the flow through the device. The simulations suggest that the performance of a single stage could be improved significantly by changing the geometry of the entrance flow. Further improvements in performance could be achieved by cascading the devices.

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## 1. Introduction

On-site quantitative analysis of volatile and semi-volatile chemical vapors is required for environmental monitoring. Normally, detecting chemical vapors relies on labor-intensive and costly sample collection followed by transport to a remote laboratory for analysis. This limits the frequency and overall quality of the measurements [1]. Meanwhile, currently available portable instruments (e.g., miniature mass spectrometers) lack the sensitivity for routine air quality monitoring [2–5]. This deficiency can be rectified by developing miniaturized pre-concentrators that can be used as front-ends for portable instruments.

The temporal response of many commonly used techniques for sensitivity enhancement, like gas chromatography, sorbent

beds, and selectively permeable polymer diaphragms [6–11], is limited by the relatively large time constants ( $\sim$ minutes) associated with adsorption/desorption or permeation of gas molecules. In addition, these techniques require temperature programming and/or consumable materials such as adsorbents that increase the complexity of device fabrication and system integration.

The objective of this work is to demonstrate a fast-response microfluidic gas concentrating device that eliminates the need for embedded electrodes, adsorbents, or membranes. The device can provide simultaneous gas concentration and separation like a centrifuge, but is much easier to be realized at the microscale. While other concentration methods take several to tens of minutes for the absorption/desorption or permeation of the gas molecules being focused, this device exhibits a fast response ( $<0.01$  ms) suitable for use as a real-time preconcentrator in miniaturized chemical sensing systems.

This paper describes the design, fabrication, and characterization of a single-stage gas concentration device. The basic

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operating principle is described, design considerations are discussed, and the fabrication process is described. Experimental procedures for measuring the device's ability to concentrate heavy gas molecules (like volatile organic vapors) under atmospheric conditions are developed based on mass spectrometry. Measurements of the device's performance are compared to the predictions of a two-dimensional computational fluid dynamics (CFD) simulation. Taken together, these results are used to develop a quantitative understanding of the separation processes occurring in the device and how the performance of the device could be improved by changing its design.

## 2. Design and fabrication

### 2.1. Operating principle

The operation of the gas concentrating device is based on the separation nozzle method originally developed for the enrichment of the uranium isotope  $^{235}\text{U}$  [12–14] where a gas mixture is divided into fractions of different compositions [14] in a continuous process. Fig. 1a is a 3-D contour image of the single-stage gas separation device. It consists of a curved converging-diverging nozzle, a deflection wall, and a skimmer. A gas mixture (e.g.,  $\text{SF}_6$  diluted in  $\text{N}_2$ ) is introduced on the left side of the image at the entrance to the curved nozzle. The mixture is accelerated by expansion in the nozzle and then deflected by the curved channel. The centripetal acceleration associated with the turning flow creates a radial pressure gradient that drives differential diffusion of  $\text{N}_2$  and  $\text{SF}_6$  in directions perpendicular to the streamlines. The heavier  $\text{SF}_6$  molecules become concentrated at the periphery of the flow field and a skimmer is used to mechanically separate the stratified gas mixture exiting the curved channel into a 'heavy' fraction that is enriched in  $\text{SF}_6$  and a 'light' fraction that is depleted in  $\text{SF}_6$  [15].

### 2.2. Separation factor

The shift in concentrations between the light and the heavy fractions is characterized by the separation factor  $A$  which is usually expressed in terms of partial cuts  $\theta_i$ . The partial cut of a component of the mixture is the percentage of its throughput in the separation element which is withdrawn in the light fraction stream [14]. For a simple binary gas mixture,  $A$  is defined as

$$A = \frac{\theta_l(1 - \theta_h)}{\theta_h(1 - \theta_l)} \quad (1)$$

where  $\theta_l$  and  $\theta_h$  are respectively the light component and heavy component partial cuts. The partial cuts can be written in terms of the mass flow rates of the heavy and light species in the heavy and light streams as follows:

$$\theta_l = \frac{\dot{m}_{l,\text{light}}}{\dot{m}_{l,\text{light}} + \dot{m}_{l,\text{heavy}}} \quad \text{and} \quad \theta_h = \frac{\dot{m}_{h,\text{light}}}{\dot{m}_{h,\text{light}} + \dot{m}_{h,\text{heavy}}} \quad (2)$$

The first subscript l or h, corresponds to the light species or the heavy species while the second subscript, 'light' or 'heavy', corresponds to the light or heavy fraction stream where the

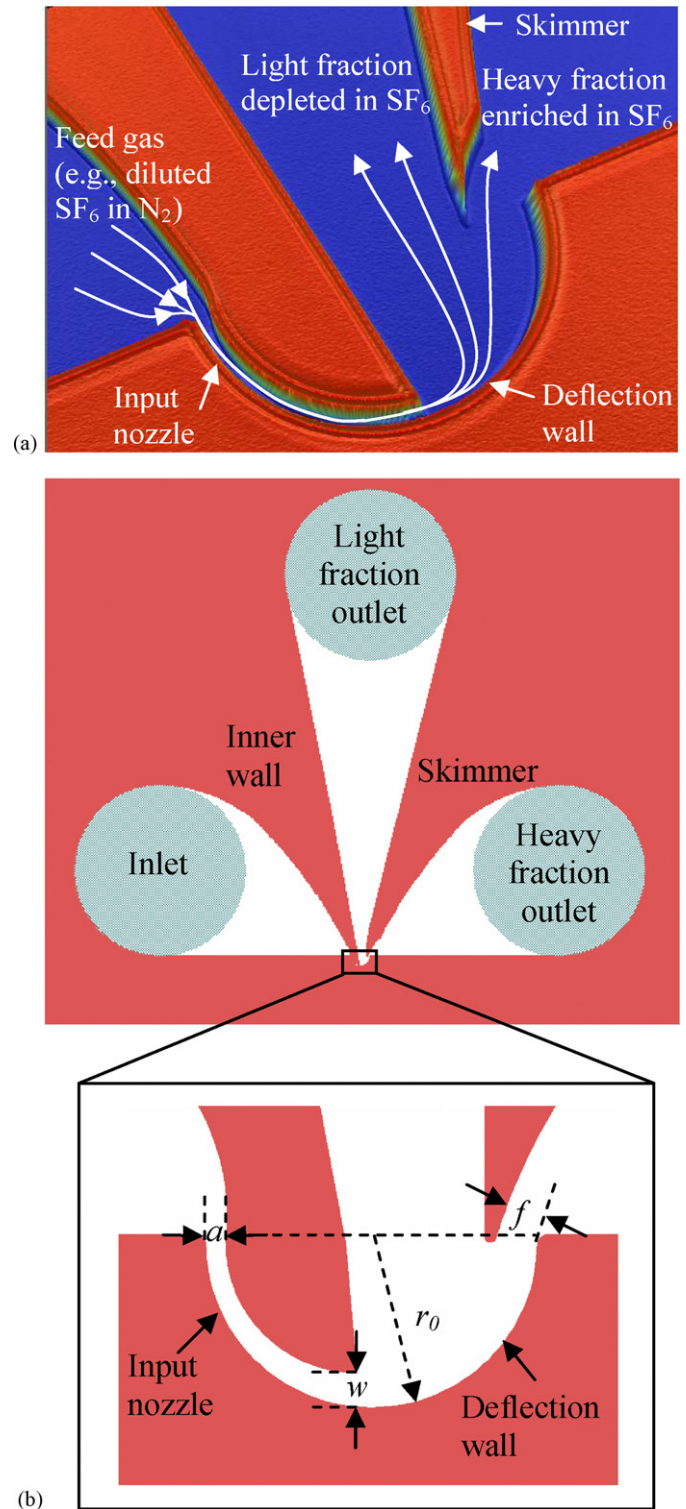


Fig. 1. (a) Three-dimensional optical profilometry surface image of a single-stage gas concentrating element; (b) schematic diagram of a microfabricated single-stage separation device showing the inlet and outlet plenums and a close-up view of the gas concentrating channel identifying the critical design parameters.

species is found. Based on these definitions, perfect separation corresponds to  $\theta_h = 0$  and  $A \rightarrow \infty$ . Therefore, the success of the design of a separation device is directly related to its ability to maximize the separation factor.

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