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Research paper

Investigation of a multistage micro gas compressor cascaded in series for increase pressure rise

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A R T I C L E I N F O

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A B S T R A C T

This paper discusses the fabrication, assembly, and testing of a single-stage and a two-stage micro gas compressor cascaded in series to demonstrate the effectiveness of a multistage serial configuration with the utilization of piezoelectric unimorph diaphragms and passive microvalves. Gas compression is enabled with the large stroke volume from the diaphragm resonance frequency of ~4.5–5.8 kHz, generating pressure rise for the single and multistage microcompressors. The microcompressors consist of passive micro check valves fabricated with SU-8 using MEMS microfabrication method and a piezo disc integrated to the CNC micromachined housings. The microcompressor pressure-flow performance curves and its performance based on the dependent parameters such as the voltage and the drive frequency are presented in this paper. The single-stage and the two-stage microcompressors operate at a low max voltage of 60 Vpp and at the resonance of the piezo diaphragm to achieve maximum pressure rise. From experimental result, maximum pressure rise of 10 kPa and a maximum flow rate of 32 standard cubic cm per min (sccm) were achieved from the single-stage device. The two-stage microcompressor showed improvement over the single-stage by generating a maximum pressure rise of 18 kPa and maintained the same maximum flow rate of 32 sccm. This was achieved with each stage operating independently at the diaphragm resonance. Additionally, we provided test results of the microvalve pressure-flow curve and test characterization of the unimorph piezo disc.

1. Introduction

Since the inception of MEMS, micropumps have been developed for transporting small volume of incompressible liquids for many miniaturized chemical and biological applications. As these efforts continue, researchers are utilizing MEMS and microfabrication methods to modify the micropump technology for gas compression. New technology such as the Joule-Thomson micro vapor compression cooling system can benefit from this development, which lack a microcompressor to meet the high pressure ratio demand. A successful micro gas compressor can allow for a portable and fully integrated micro cryogenic cooler (MCC) for many cooling applications. Micro cooling enhances the performance in microelectronic devices through the reduction of thermal noises, improvement in the signal-to-noise ratios and power consumption. Super conducting magnets, laptop cooling, infrared sensors, and micro satellites are devices that can benefit from a micro cooler.

Previous groups that have developed micro gas pumps and microcompressors have utilized stacked piezoelectric actuator [1,2], piezoelectric diaphragm [3], and electrostatic diaphragm actuation [4,5] for mechanical compression. Research groups from the University of Michigan [6–9] have developed multistage micro gas pump with active microvalves to increase pressure rise. Multistage electrostatic diaphragm pump can generate high pressure but at the expense of high operation voltage in the 1000 V range for the electrostatic force to overcome the back pressure. There are also limitation of the thin diaphragm material which can strain under high pressure load. Study by Yoon et al. [10] has shown two individual micro gas pumps cascaded in series with a connecting tube to increase the pressure rise. Literature review shows no integrated multistage micro gas compressor that utilizes piezoelectric diaphragm with passive micro check valves have been developed. Additionally, its characteristics and performances are not well understood. Here we develop a multistage microcompressor that utilizes piezoelectric unimorph diaphragm and passive micro check valves to increase the pressure rise.

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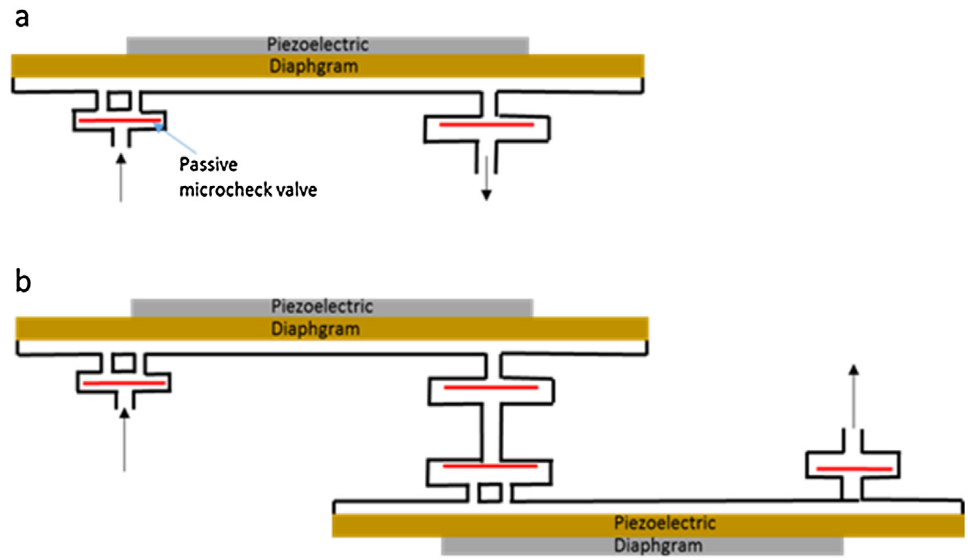

Fig. 1. (a) single-stage microcompressor schematic. (b) Multistage, two-stage, microcompressor schematic.

2. Principle of operation

A schematic of the single stage microcompressor is shown in Fig. 1a, which consists of a piezoelectric diaphragm and two passive micro check valves, each for the inlet and outlet port. The piezoelectric diaphragm is in a unimorph configuration and actuated with bipolar sine voltage up to 60 Vpp to deform the membrane for mechanical gas suction and compression in the chamber. In the suction phase, the membrane bends upward to expand the volume of the chamber and creates a negative pressure difference, causing the inlet microvalve to open and allow gas to flow into the inlet port, and causes the outlet microvalve to close, preventing gas back flow. In the compression phase, the membrane bends downward to minimize the volume in the chamber, compressing the gas, creating positive pressure difference in the chamber for the inlet valve to close and the outlet valve to open. With sine wave input frequency, the cycle repeats to generate gas flow and pressure rise through the compressor. The pressure ratio is given as

$$\frac{P_o}{P_{in}} = \left(\frac{V_{max}}{V_{min}}\right)^n \qquad (1)$$

where P_o, P_{in}, $V_{\max}$, $V_{\min}$, and n, are the outlet pressure and inlet pressure of the microvalve, maximum volume, minimum volume of the chamber and polytropic constant of the gas. Here $V_{\max} = V_{stroke} + V_{\min}$, where V_{stroke} is the stroke volume generated from the deformation of the diaphragm and $V_{\min}$ is the dead volume of the chamber. $V_{\min}$ is the uncompressed volume in the chamber and is considered as the dead volume. To develop large pressure ratio, large stroke volume is needed to increase V_{max} and minimal dead volume is needed to decrease $V_{\min}$.

For a multiple stage compressor, the pressure ratio is given as

$$\frac{(P_o)_M}{(P_{in})} = \prod_{j=1}^{M}\left(\frac{V_{maxj}}{V_{minj}}\right)^n \qquad (2)$$

where, M, is the maximum number of stages for the system, and j is stage number.

The two-stage microcompressor utilizes the same operation principle as the 1-stage as shown in Fig. 1b schematic; which consists of two pump chambers, with each having its own inlet and outlet microvalves and piezoelectric membrane. This allows for each chamber to have the ability to tune to its own resonance frequency and generate its own local maximum pressure rise in each stage, contributing to the overall pressure rise of the device.

2.1. Models and design parameters

The pressure, P_c in the chamber relating the volume of the chamber, gas flow in and out of the chamber is derived from the conservation of mass and momentum [11] and is given as

$$\frac{dP_c}{dt} = \frac{-nP_c}{V_c}\frac{dV_c}{dt} + \frac{nP_c}{\rho_c V_c}(\dot{m}_{in} - \dot{m}_{out}) \qquad (3)$$

where ρ_c, $\dot{m}_{in}$, $\dot{m}_{out}$, and V_c, are the gas density, mass flow rate in, mass flow rate out and volume of the chamber respectively.

3. Design

3.1. Single stage design

The single-stage microcompressor design is shown in Figs. 2 and 3. The piezoelectric unimorph diaphragm is a Ø 20 mm × 0.21 mm thick piezo disc buzzer and is sealed with a Ø 1 mm thick × Ø 18 mm ID O-ring placed in between the piezo disc and chamber surface. The piezo disc is clamped with a ring plate held together with screws and nuts, providing easy access and interchangeability to the chamber and piezo disc during testing. The piezo disc is chosen for its ease of use, low power consumption, low drive voltage, availability and low cost. Passive microvalves are used to reduce the complexity of the operation, fabrication, and assembly of the microcompressor. The micro check valves were fabricated from SU8 using MEMS microfabrication method, released from a silicon wafer substrate, and UV-glued to the outlet and inlet valve seat of the compressor housing. The housing was CNC machined from acrylic material.

Piezo disc generate small swept to dead volume ratio, which leads to low pressure rise. Efforts to reduce the dead volume in the chamber were conducted to maximize the pressure rise performance of the compressor with the design of a flat chamber surface. The chamber surface was machined flat as possible with a fly cutter tool using a Tormach CNC machine. The inlet and outlet port diameters were minimized to reduce dead volume without sacrificing too much pressure loss from a small diameter hole. The radius ratio of the inlet to the valve plate was minimized to increase the sealing