3-D PRINTED MINIATURIZED DIAPHRAGM VACUUM PUMP

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ABSTRACT

This paper reports the first demonstration of a fully additively manufactured, miniature diaphragm vacuum pump. Using polyjet 3-D printing technology with 42 µm XY pixelation and 25 µm layer height, a single-stage vacuum pump design with active valves that has a total pumping volume of 1 cm^3 with 5% dead volume was implemented. While operating at 3.27 Hz, the devices consistently pumped down from atmospheric pressure to 330 Torr in under 50 seconds (8.7 cm^3/min effective flow rate, which is >300X the highest reported flow rate from a diaphragm vacuum pump manufactured with standard microfabrication). Finite element simulations of the pump design estimate at 100 kPa the maximum stress on the piston diaphragm root at full actuation, and at 42 Hz the natural frequency of the compression chamber. Compression chamber diaphragms exhibited lifetimes approaching 20,000 cycles, while the valves membranes have not leaked after over 1,000,000 cycles.

INTRODUCTION

Miniaturized pumps supply fluids at precise flow rates and pressure levels in a wide variety of microfluidic systems. In particular, microfabricated positive displacement pumps that exploit gas compressibility to create vacuum have been reported as a first pumping stage in non-zero flow, reduced-pressure miniaturized systems, such as mass spectrometers [1]. However, the mass flow rate versus pressure performance of positive displacement vacuum pumps manufactured with standard microfabrication is limited by their large dead volume compared to the total pump volume [2], while their expensive manufacture is incompatible with low-cost applications. Compared to standard microfabrication, additive manufacturing offers the advantages of rapid prototyping, larger displacements for better vacuum generation and larger flow rate, freeform geometries, and a broader material selection, while attaining minimum feature sizes on par with microfluidic systems (out-of-plane features in the 10-300 µm range and in-plane features in the 25 – 500 µm range). In addition, a number of 3-D printing techniques make possible the definition of leak tight, closed channels or cavities, sometimes involving a second sacrificial material that is removed after printing. Examples of 3-D printed microfluidic devices exist –including pumps for incompressible liquids [3]-[7], but to the best of the authors' knowledge no 3-D printed MEMS diaphragm pumps for vacuum generation have been reported.

DEVICE DESIGN

A computer-aided design (CAD) model of the single-stage diaphragm pump is shown in Figure 1. The 24 mm-wide, 35 mm-long, and 24 mm-tall device has a total pumping volume of 1 cm^3 with 5% dead volume and consists of a compression chamber and two active valves. The compression chamber is composed of a 12.8 mm diameter piston surrounded by a 1 mm-thick diaphragm, and each valve is a 4 mm diameter piston surrounded by a 1 mm-thick membrane. The base of the compression chamber is 20 mm in diameter and the sidewalls are bowed to minimize the dead volume upon compression. The design incorporated fillets at the edges with the highest stresses. The pump creates vacuum by removing pockets of gas from a cavity, compressing them, and releasing them to a reservoir at high pressure.

Finite element simulations of the compression chamber design were conducted using the commercial software Solidworks 2015 and the mechanical properties of the printable material TangoBlack Plus® (Young's modulus equal to 0.3 MPa and tensile strength equal to 0.8 MPa [8]-[10]). Figure 2 shows an oscillation amplitude field from the frequency analysis of the piston structure (the units of the amplitude field are arbitrary). From these simulations, the natural frequency of the piston is estimated at 42 Hz. Figure 3 shows a cross-section of the stress field (in kPa) from the static stress simulation of the piston. The maximum stress is

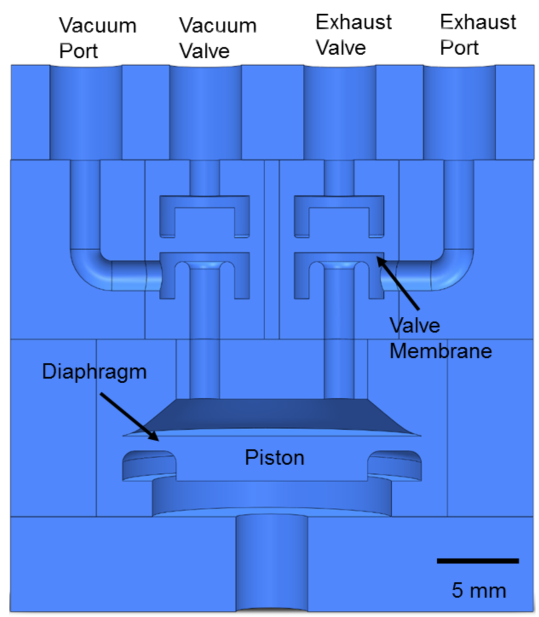

Figure 1: Cross-section of a CAD model of the pump.

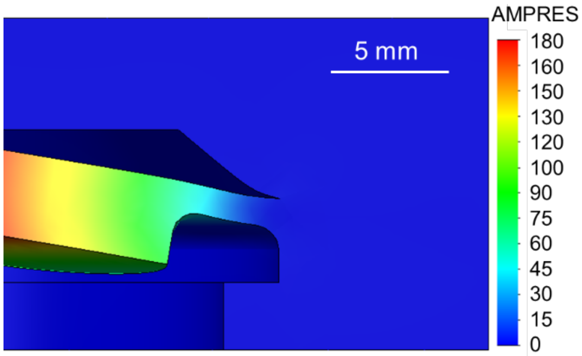

Figure 2: Simulation results of the oscillation amplitude field during resonance of the pump piston (42 Hz).

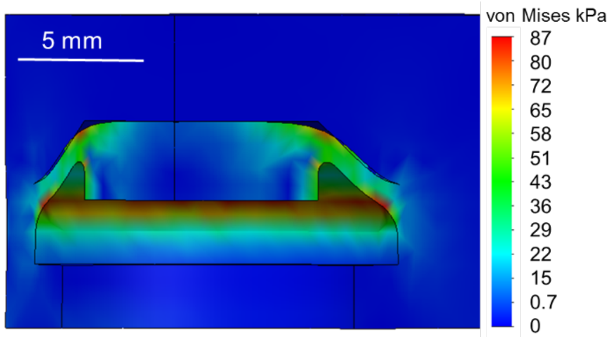

Figure 3: Simulation results of the finite element stress analysis of the piston at full actuation.

at the root of the diaphragm, i.e., the edge at which the diaphragm is attached to the compression chamber. The maximum stress is estimated at 100 kPa, which is well below the 800 kPa lower bound of the tensile strength of the material [10]. The compression chamber was designed to allow for a maximum diaphragm elongation of 20%, which corresponds to the suggested maximum elongation to avoid failure by fatigue [11].

DEVICE FABRICATION

Flexible, thin, and leak tight membranes are essential to implement a positive displacement diaphragm vacuum pump; therefore, the ability to 3-D print these structures is critical. However, many of the 3-D printing technologies require further refinement to attain such specifications, and improvement of the mechanical properties of the printable materials is also needed [12]. For manufacturing the pump, three 3-D printing methods with a high degree of maturity that could yield nonporous solid structures with embedded channels were considered: (i) fused filament formation (FFF), i.e., a manufacturing method that creates layer by layer freeform solids by extruding a thermoplastic filament; (ii) digital light processing stereolithography (DLP-SLA), i.e., a manufacturing method that creates layer by layer freeform solids using a bath of UV-sensitive resin; and (iii) polyjet, i.e., a manufacturing method similar to inkjet printing that creates layer by layer freeform solids by UV curing droplets of liquid photopolymer that are jetted on a build tray. Flexible and thin membranes can be 3-D printed by the FFF method; however, an earlier version of the pump design that was made with the Ninjaflex® thermoplastic polymer [13] did not have leak tight membranes. We also investigated using DLP-SLA because microfluidic valves made by this method with up to 1-million cycles have been reported [6]; however, the maximum reported elongation of the photopolymers used in DLP-SLA is not as large as that of the flexible materials available for the polyjet method, which limits the ultimate pressure that can be attained by the diaphragm vacuum pump as it depends on the compression ratio of its chamber. In particular, while a maximum elongation of ~85% can be achieved by the DLP-SLA-printable material FLFLGR02 [14], up to 220% of maximum elongation without failure can be achieved by the polyjet-printable material TangoBlack Plus® [10].

The diaphragm pumps were polyjet 3-D printed in the flexible photo-definable polymer TangoBlack Plus® using 42 µm-wide, 42 µm-long, and 25 µm-tall voxels; the printable sacrificial material FullCure® 705 temporarily filled-in internal cavities of the pump during manufacturing. The sacrificial material was removed using a solution of 2% NaOH in H_2O and mechanical agitation. Printing the pump in two halves facilitated ease of removal of the sacrificial material; the two halves connect at the line drawn through the middle of the diagram in Figure 1. The lower half contains the compression chamber, while the upper half houses the vacuum and exhaust valves along with the inlet and outlet pipe network. Arrangement of the four ports on top of the pump in a linear array with sufficient spacing allowed for using miniature brass pipe fittings barbed for 1/8" tubing.

EXPERIMENTAL SETUP

The apparatus shown in Figure 4 was used to characterize the pumps. A top aluminum plate and a bottom acrylic plate held the printed piston and valve assemblies together with nuts and bolts. The pump required to be compressed by 17% (4 mm) to prevent leakage at the plate/pump interfaces; unfortunately, this procedure has the

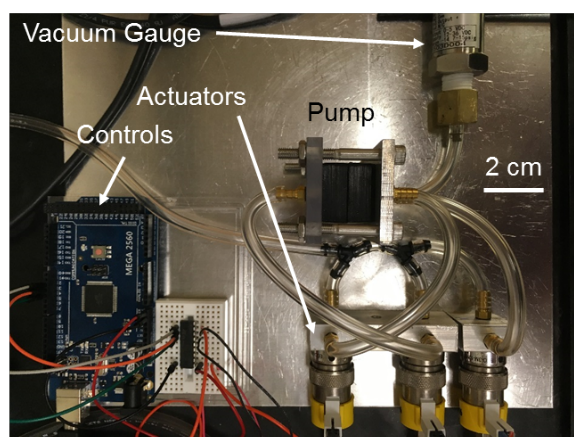

Figure 4: Photograph of the testing rig.

Table 1: *Diaphragm and valve actuation sequencing.*

Step	Delay (ms)	Diaphragm	Vacuum Valve	Exhaust Valve
State 1	10	Retracted	Closed	Open
Exhaust	143	Compressed	Closed	Open
State 2	10	Compressed	Open	Closed
Evacuate	143	Retracted	Open	Closed
Repeat				

collateral effect of reducing the displacement of the compression chamber piston and increasing the relative size of the pump dead volume.

The acrylic plate has one threaded hole to accommodate a miniature brass fitting with o-ring for actuation of the chamber piston. The clear acrylic plate is used as a window to observe the extent of displacement of the piston as the N_2 supply pressure is varied to optimize the stroke. The top plate has four threaded holes: the outer two for vacuum and exhaust ports, and the inner two for vacuum and exhaust valve actuation. Three-way solenoid valves (Clippard, model EC-3M-12-H) with a response time of 10 ms are used for valve and diaphragm pneumatic operation. Compressed nitrogen is fed to one side of the solenoid valves, house vacuum to the other side, and 1/8" Tygon tubing is plumbed from the barbed fittings on the plates to the solenoid valves.

The pump exhausts to atmosphere and the vacuum port is plumbed to a pressure gauge with an accuracy of +/-15 Torr (Transducers direct, model TDH31, vacuum to 15 psi range). The effective vacuum chamber volume is 1 cm^3; this volume includes the pressure transducer volume, the pipework and fittings, and the printed vacuum valve volume.

The solenoid valves are controlled with an Arduino micro controller (Mega 2560) programmed to supply pressurized N_2 or house vacuum to the pump valves and diaphragm. The pumping performance is optimized by adjusting the timing of the valves and N2 pressure. Table 1 contains the sequencing and delay times used. During pump testing, a Dataq DI-149 datalogger collected voltage signals from the pressure transducer at a rate of 8 Hz. The piston and valves are activated pneumatically with pressurized nitrogen regulated to 11 psi and house vacuum of 270 Torr (9.5 psi).

EXPERIMENTAL RESULTS

The printed devices consistently pumped down a 1 cm^3 volume from atmospheric pressure to 330 Torr in under 50 seconds operating at 3.27 Hz (Figure 5). Ideally, with a 5% dead volume, no leaks, and no issues with valve actuation, the expected ultimate pressure is about 40 Torr (i.e., 0.05*760 Torr). The ultimate pressure of the pump is limited by the house vacuum used to hold the valves open (when the pressure in the compression chamber of the vacuum pump drops below 270 Torr, the valve actuation mechanism ceases to function).

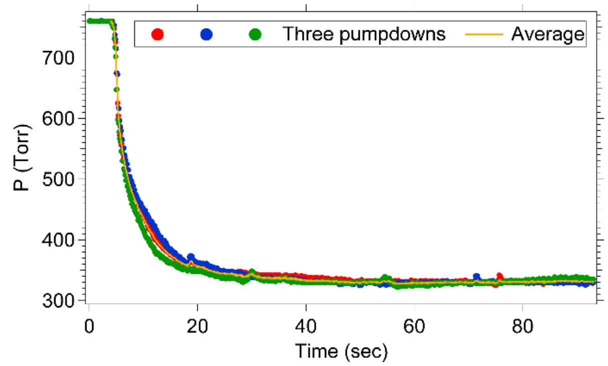

Figure 5: Vacuum port pressure vs. time for several pump downs and average pump down, 3.27 Hz actuation.

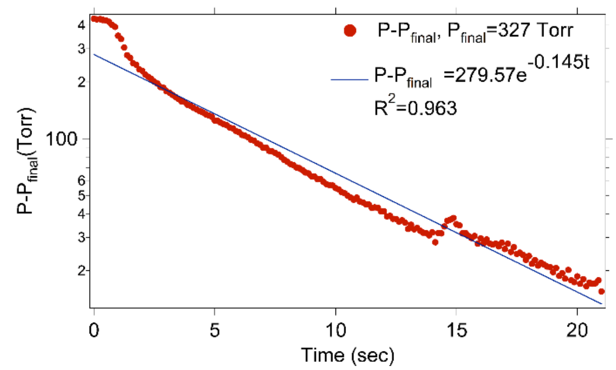

Figure 6: Semi-log plot of $P-P_{final}$ vs. time of the averaged data shown in Figure 5. Data in red, exponential curve fit in blue with exponent S_{eff}/V, $V=1$ cm^3, $S_{eff}=0.145$ cm^3/s.

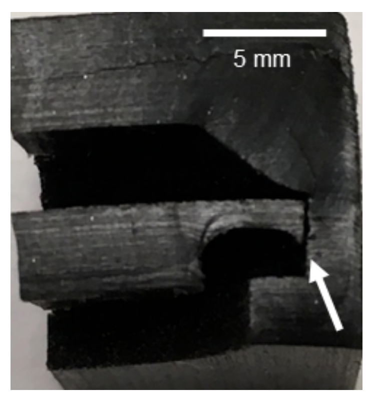

Figure 7: Close-up of the root of a failed diaphragm

An effective flow rate of 8.7 cm^3/min is obtained from analyzing the pump data (Figure 6), which is >300X the highest reported flow rate from a diaphragm vacuum pump manufactured with standard microfabrication [1].

The compression chamber diaphragms exhibited lifetimes approaching 20,000 cycles, while the valves membranes have not leaked after >1-million cycles. As predicted by the finite element simulations, the failed diaphragms show cracks at their root, which is the point of maximum stress (Figure 7).

CONCLUSIONS

This paper reports the first demonstration of a fully additively manufactured, miniature diaphragm vacuum pump. A single-stage vacuum pump design with active valves that has a total pumping volume of 1 cm^3 with 5% dead volume was 3-D printed by the polyjet method using 42 µm-wide, 42 µm-long, and 25 µm-tall voxels, the structural material TangoBlack Plus®, and the sacrificial material FullCure® 705. While operating at 3.27 Hz, the devices consistently pumped down from atmospheric pressure to 330 Torr in under 50 seconds (8.7 cm^3/min effective flow rate, i.e., >300X the highest reported flow rate from a diaphragm vacuum pump manufactured with standard microfabrication). Compression chamber diaphragms exhibited lifetimes approaching 20,000 cycles, while the valves have not leaked after >1-million cycles. Current work is focused on increasing the diaphragm lifetime, reducing the ultimate pressure, and improving the mass flow rate versus pressure characteristics of the pump.

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