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3D printed lost-wax casted soft silicone monoblocks enable heart-inspired pumping by internal combustion

Christoph M. Schumacher,[a] Michael Loepfe,[a] Roland Fuhrer,[b] Robert N. Grass[a] and Wendelin J. Stark [a,*]

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We present a gas combustion powered soft pump made from highly durable and flexible polydimethylsilioxane (soft silicone). Our soft pump was able to run for 10,000 combustion cycles at a constant combustion power rating of 500 watts and thus discloses novel prospects for longlasting soft-machines at high specific energy-densities.

Today's engines are essentially adapted from rigid parts. This inevitably results from the use of moving parts, bearing substantial mechanical load at considerable power density,[1, 2] which usually have to be kept within very narrow dimensional margins. In nature, the structural integrity of many developed organisms is maintained by e.g. chitin or bones.[3, 4] In contrast, some organisms (e.g. worms and slugs) and a lot of constituents in animate systems even get along completely without any solids (i.e. a heart muscle).[5, 6] Such soft systems provide the fundamental advantage of high flexibility with good running features even under considerable deformation at comparably low weight.[7-9] Here however, classical engineering concepts such as torque transmission are of limited validity and thus put contraction and expansion forward. Advances in robotics have revealed fascinating prospects in soft machining for locomotion or grabbing. The prevalent mobilization method is based on pneumatics,[10-12] however also stimulation by electric charge[13-18] and magnetic fields[19] have been elaborate. Recently, Whitesides et al. have pointed out that internal combustion in soft structures (by methane – oxygen mixtures) can substantially enhance actuation response and power characteristics compared to common approaches by e.g. pressurized air.[20] Hydrocarbon based energy carriers are very lightweight compared to other power sources such as batteries.[21]

Here, we demonstrate a combustion powered soft pump capable of conveying water up to a back-pressure of 0.1 bar (75 mmHg). This bioinspired pump was able to run for >10'000 combustion cycles in series by imitating heart-like chamber squeezing. Concretely, we fabricated injection molds from poly(acrylonitrile-co-butadiene-co-styrene) (ABS) using 3D printing technology into which we injected vulcanizing silicone elastomer mixture. After curing at room temperature, the filled molds were dissolved in acetone, leaving otherwise hardly accessible silicone elastomer structures. Appropriate polydimethylsiloxane (PDMS) elastomers are known to withstand extensive thermal and mechanical stress.[22, 23] The here used material accounts for up to 1000 % elongation at break. Our proposed monoblock manufacturing technique (i.e. no separate parts) avoids weak spots such as bonding surfaces, which can incisively depress life-time and durability of the structures. The soft pump (see Fig. 1, ESI Movie S1†) consists of two outer combustion chambers (volume of 75 cm^3, each), which are separated from two individual inner liquid chambers (volume of 80 cm^3, each) by 3 mm thick actuation barriers. Upon combustion, these flexible barriers expand inwards and displace the liquid. Flow directing check valves connected to the inlet and outlets of the pumping chambers enable clocked pumping. To maintain a combustible environment, we continuously fed an air – methane mixture at a volumetric ratio of 10:1 (and thus slight oxygen excess) through tubing into the combustion chambers. To prevent any backdraft, flame arresters were connected to these. Ignition by inserted spark gaps was automated by a programmable logic controller. As a result of the gas expansion by combustion, the silicone relaxation and the continuous fresh gas feed, exhaust gases were ejected through holes in the combustion chamber side walls. Their small diameter allowed a sufficient pressure increase during the temporally short combustion

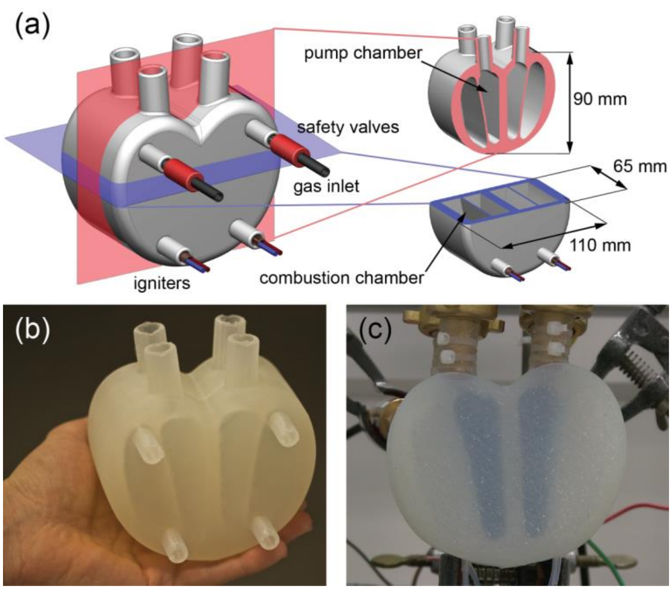

Fig 1. Bioinspired soft pump for imitating heart-like chamber squeezing: (a) Scheme and dimensions of the silicone internal combustion pump. A thick wall houses two outer combustion chambers with fuel gas supplies, spark gap ignition connectors and thin exhaust holes connected to Teflon tubing on the lower side. In the core, two individual liquid chambers with inlet/outlet ducts are actuated through thin walls by combustion gas expansion. (b) An injection molded monoblock silicone pump. (c) Front view of the soft pump in the experimental setup, the gas inlets and spark-gap igniters are connected at the back-side, exhaust Teflon tubings are attached on the lower side and liquid ducts connected to the pumping chambers lead to check valves at the top right above the depicted brass fittings (for entire setup also see ESI Fig. S2).

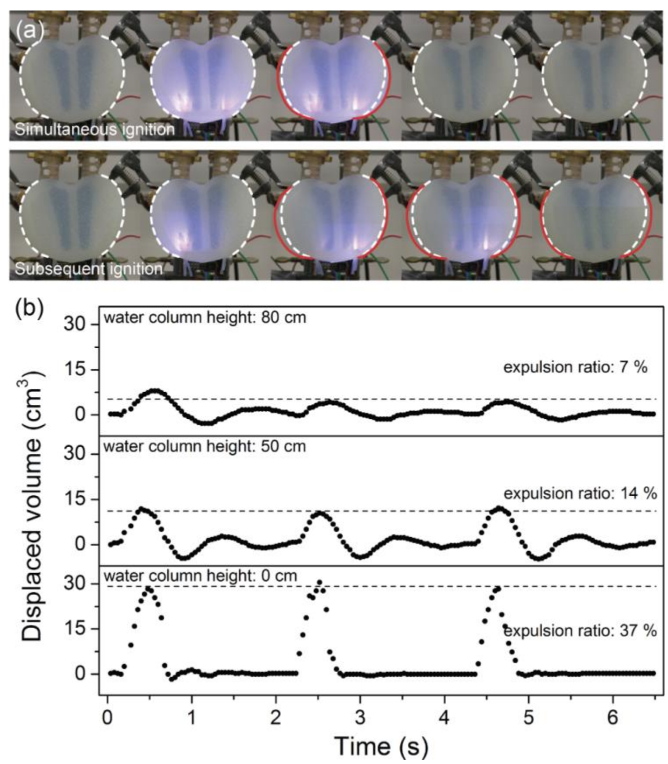

Fig 2. Working cycles of the combustion soft pump: (a) Ignition pulse picture series with both simultaneous and subsequent combustion chamber ignition. Each sequence lasts for around 0.25 seconds. The combustion gas expansion leads to a pumping membrane actuation, visible by the deformation of the liquid chambers. The entire soft silicone structure expands, visualized by the drawn reference lines. (b) Displaced liquid volumes in dependence of the back pressure by water heads differing in height. The expulsed volume decreases with a raising water column that has to be lifted. The ratio between a liquid chamber volume (80 cm^3) and the averaged displaced liquid volume is denoted as expulsion ratio.

actuation, though also adequate off gas release rates thereafter. Since the here presented soft pump has got a much higher combustion chamber volume to actuated surface ratio, a pure oxygen – methane combustion would lead to disproportionate peak pressures with potential damage of the silicone structure. This stays in contrast to the previous report by Whitesides et al.[20] Using the buffering properties of air (respectively those of the contained inert gases) enables the generation of a smoother pump actuation by slower combustions.[24] This not only conserves the silicone structure, but also promotes increased liquid expulsions since the inertia of water counteracts too rapid actuations. The refractory period of the here presented soft pump after an ignition pulse is mainly controlled by fresh gas charging, whereas the recovery of the initial silicone shape appeared to take only around 0.15 seconds. Chamber actuation was executed both simultaneously and with a time delay of 0.1 seconds (Fig. 2a, ESI Movie S2, S3). The hot combustion gases lead to an expulsion of the liquid chambers and slightly expand the whole silicone structure as well. Since the conveyed liquid volume per pulse is dependent on the counter pressure at the outlet, we also monitored the expulsed water amount in dependence of different water head heights (Fig. 2b, ESI Movie S4). Water displacement was possible up to a water column of 1 meter in height. Combustion gas flows were adjusted in such a manner that from a calculation point of view all the gas can be substituted until the next ignition. The amount of methane contained inside a combustion chamber amounts to 0.28 mmol (4.5 mg). Therefore, a pulse releases approximately 250 J of thermal energy (for detailed calculations see Supplementary Information). At a pumping frequency of 60 beats per minute, the total power output amounts to 500 W for both actuation chambers (32.4 g methane consumption per hour). Nevertheless, regarding the conveyed water mass, the energy efficiency is however as low as only 0.03% (see thermodynamic calculations in ESI). In a worst-case scenario test without additional cooling by pumped liquid, the combustion side walls heated up to over 200 °C after prolonged actuation (Fig. 3a, d). This puts the PDMS material under substantial oxidative stress. Consequently, a thin silicium dioxide layer deposits on the combustion chamber surface (Fig 3b). The composition was verified by diffuse reflectance fourier transform infrared spectroscopy (DRIFTS) (Fig. 3e). This oxide layer consists of sub-micron sized particles in the range of 100 – 300 nm according to scanning electron microscopy (SEM) imaging (Fig. 3c, f). A part of this fine degradation powder was observed to escape from the combustion chamber through the gas exhaust holes (visible deposits). Despite the combustion chamber side walls are heating up to over 200 °C after prolonged actuation, the degradation by silicon dioxide formation proceeds very slowly. Even after 10’000 ignitions, the actuation barriers remained flexible and structurally intact with a still thin oxide layer (< 0.1 mm). A partial explanation for this impressive resistance could result from the good heat insulating properties of silicon dioxide layers.[25, 26] On the other hand, it is an everyday phenomenon that a human finger can be passed back and forth through a flame without risking burns when executed at sufficient pace. Rapid combustion (within approximately 50

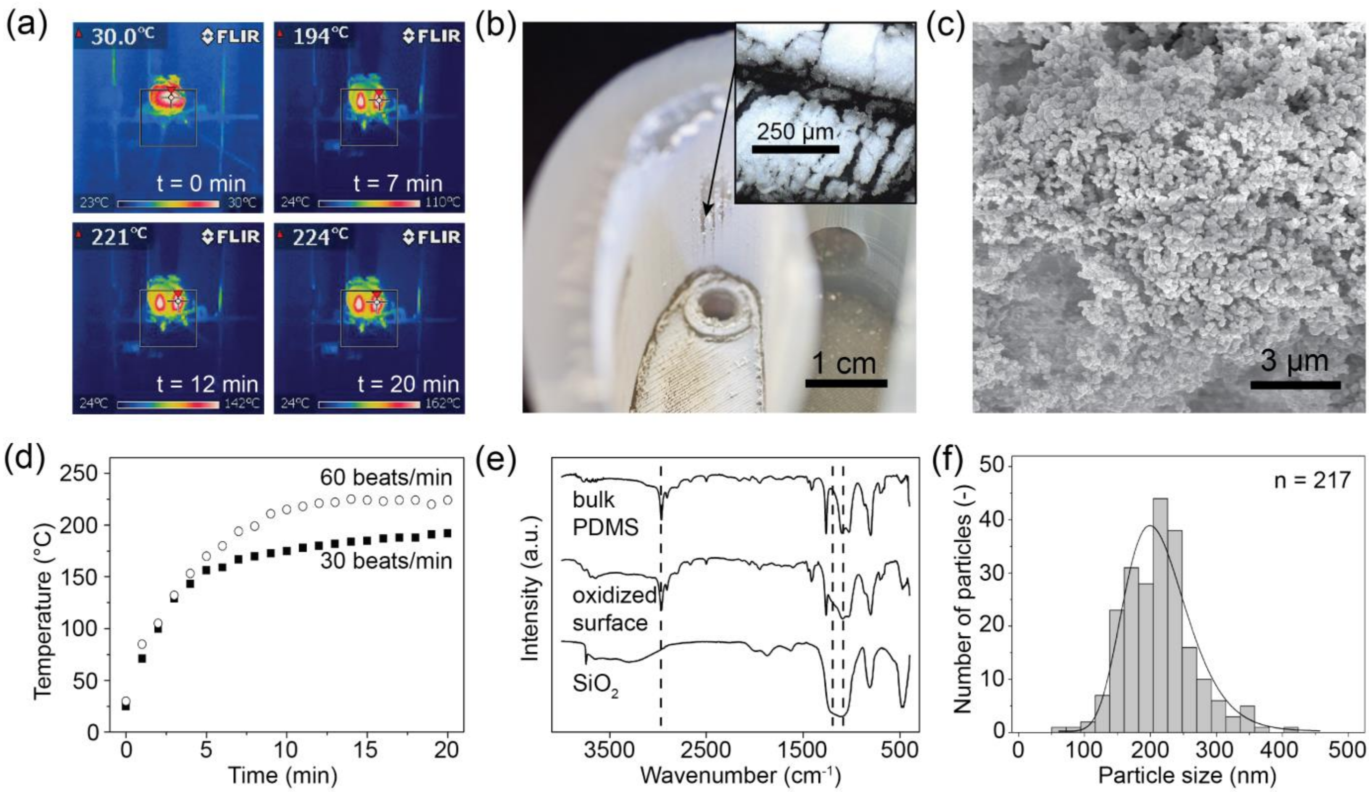

Fig. 3. Temperature evolution and material stability in a worst case scenario with no conveyed liquid: (a) Infrared thermal camera images of the soft pump during pumping at a pumping frequency of 60 beats per minute. A steady state operation temperature is reached at 220 °C. (b) Continuous gas combustions in the actuation chambers lead to PDMS degradation (here: after 3’000 ignitions) and deposition of a thin silicon dioxide layer. Light microscopy imaging shows brittle glass-like depositions. (c) Scanning electron microscopy surface imaging reveals the formation of sub-micron sized particles. (d) Temperature evolution of the combustion chamber side walls at different actuation frequencies. Steady operation temperatures are reached after approximately 10 to 15 minutes. Even in the case of 60 beats per minute, the maximally reached temperature remained approximately 100 °C below the PDMS degradation temperature of 320 °C (determined by thermogravimetric analysis). (e) The appearance of an overlapping broad band at 1200 cm-1 (reference: pure silicon dioxide) in the diffuse reflectance Fourier transform infrared spectrum of the oxidized PDMS combustion chamber surface confirms the formation of silicon dioxide upon continuous operation. (f) The particle size distribution of the formed silicon dioxide particles (Scanning electron microscopy image analysis, median 210 nm).

ms) creates similar circumstances in the here presented soft pump. Nevertheless, considerable amounts of heat are generated. The pumped liquid as well as exhaust gases remove a decent part of the generated heat. Even

though PDMS exhibits relatively poor heat conductivity and therefore restrains passive cooling by surrounding air and pumped liquid, the maximally reached operation temperatures are significantly below the material degradation temperature of 320 °C. This was also determined using thermogravimetric analysis (ESI Fig. S5). We expect that the thermal load for such a soft machine could be further raised if additional channels for cooling liquid would be added to the PDMS structure.

Conclusions

Summarizing, we have shown a technique to manufacture soft PDMS pumps that use gas combustion for actuation and cope with considerable power densities (up to 1000 watts per liter machine volume). Gases for fueling are cheap and very lightweight energy carriers. It pointed out that monoblock structures are critical for long-term stability for several thousands of internal combustions (i.e. flexible structure must be manufactured as a single piece in order to avoid weak spots). Similar circumstances can for example be found in car tires, where the rubber must always be vulcanized to a single part. The good running characteristics of our soft pump even under considerable deformation create promising perspectives for robotics, implants or prostheses. We expect that combination with even more durable materials (re-inforced rubbers or similar) could further enable even more robust soft machines with expanded lifetimes and higher power-densities. Our pump however shows a low conveyance efficiency (determined as 0.03%) regarding energy supply by combustible gas mixtures. Besides thermal deprivation, a lot of the combustion energy is lost by undesirable structural displacement of the soft silicone. Avoiding these dissipative expansion movements is therefore crucial for future applications.

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the design of the injection molding press. All authors elaborated the concept for high power density soft pumps. C.M.S. and M.L. designed the detailed setups and conducted the experiments. R.F. developed the RTV silicone injection molding technique. C.M.S., M.L. and W.J.S. analysed the data and wrote the paper.

Notes and references

[a] Institute for Chemical and Bioengineering, Wolfgang-Pauli-Strasse 10, CH-8093 Zurich, Switzerland.

[b] Nanograde Ltd., Laubisruetistrasse 50, CH-8712 Staefa, Switzerland.

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