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Rapid Soft Material Actuation through Droplet Evaporation

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Soft material actuation is a promising field that can potentially solve several limitations of traditional robotic systems. These systems are composed of soft and flexible materials to achieve high degrees-of-freedom and compliance with its surroundings. One method to actuate such structures is to vaporize liquid that is embedded inside the soft material. The soft elastomers are inflated, since the generated vapor occupies a much larger volume after phase transformation. The simplest and widely used design to vaporize such liquids is by installing a heating element near the liquid. Heating the system beyond the boiling point rapidly boils the liquid and deforms the structure. However, this technique possesses several limitations, where the heating element must be in the liquid's vicinity, and boiling the liquid requires high temperatures. In addition, embedding a small amount of liquid for faster boiling prevents the use of valves to exhaust the vapor. Instead, the structure is slowly cooled until it returns to its original position. In this study, these limitations are addressed by combining heating with vibrating mesh atomization. The atomizer disperses the liquid into small droplets, which vaporize much faster as compared to simply heating the bulk liquid. Actuation through vibrating mesh atomization was first characterized and compared with other techniques. Then, the introduced method was used to demonstrate cyclic actuation, and a bistable structure was designed and fabricated to demonstrate gripping motion.

Keywords: Bistable structures, phase transformation, piezoelectric, vaporization, vibrating mesh atomization.

Introduction

Soft actuation through liquid-to-gas phase transformation is receiving significant attention due to its possibility of replacing pneumatic pumps.[1-5] Since typical pneumatically actuated soft structures require the system to be tethered to a heavy and bulky pump, actuation through vaporization can simplify and miniaturize system setup. In most cases, actuation is achieved by vaporizing liquid inside a soft elastomer. These liquids with low boiling temperatures are filled inside cavities or chambers that are strategically located inside the structure. Heating of the liquid is generally achieved by injecting current through joule heating elements embedded in the system. At temperatures below boiling, liquid evaporates only at the surface until its vapor pressure reaches equilibrium. When the structure reaches boiling, however, the entire bulk liquid starts to boil and vaporizes much faster. It is preferred to boil the liquid for rapid vaporization, as evaporation is highly dependent on surface area.[6] The generated vapor during this phase transformation inflates the chamber and deforms the overall structure.

Actuation through vaporization is a complicated process that is affected by various parameters, since the overall process is a combination of thermodynamics, kinetics, and mechanics. The vapor pressure of the liquid, efficiency of the heater, and thermal conductivity of the structure are just some of the specifications that control and influence the vaporization process. As a result, simulations and experiments for optimizing system performance can be challenging. In addition, even though measuring temperature is as simple as attaching a thermocouple to the system, further analysis involving heat (*e.g.*, heat transfer or latent heat) requires more complicated setups.[7] However, the complexity of this multi-physics process also indicates that there is considerable potential for improvement. Various studies have addressed or utilized some of these parameters with the universal goal of improving actuation.[1, 2, 5, 8]

One of the most straightforward methods of increasing actuation performance is to select a liquid with a low boiling temperature.[9] Higher vapor pressure is directly related to the amount of gas that is generated inside the structure. For example, heating acetone (with a boiling point of 56 °C) generates more vapor as compared to heating ethanol (with a boiling point of 78 °C) with the same heater for a given amount of time. When all other conditions are fixed, higher vaporization rate results in higher actuation speed, blocking stress, and efficiency. Only a small amount of liquid is required to inflate these structures, since, theoretically, one mole of liquid vaporizes into 22.4 L of gas under standard temperature and pressure (STP) condition.[1, 5] During materials selection, it is also important to choose a liquid that is environmentally safe and does not react with other materials in the system. Boyvat *et al.*[2] introduced a novel actuation method through inductor-capacitor resonant receivers. The untethered bellows structure was heated and expanded when placed in an external magnetic field. In order to maximize actuation speed and blocking stress, a liquid with a boiling point as low as 34 °C was used.

After selecting the type of liquid, the ability of the structure to store heat can also greatly affect actuation performance. When the heater is installed inside the structure, it will take a longer time to reach the boiling temperature if most of the heat dissipates to its surroundings. Thus, thermally insulating the inner chamber is preferred and often necessary. However, this also prevents the structure from cooling down after actuation, which increases the time for the reversing process. This slow reversing mechanism is one of the limitations of actuation systems that employ phase transformation. Instead, actuation through pneumatic pumps utilizes valves to release pressurized gas. Since a small amount of liquid is used for conventional actuation through boiling, exhausting the vapor will prevent repeated actuation. In general, increasing the thermal conductivity to improve this cooling process is more beneficial if the applied heat is high enough to rapidly boil the liquid. In order to control thermal conductivity, Oh *et al.*[5] embedded microcapsules of liquid metal inside the structure. In this example, heating was provided from the exterior of the structure. Thus, increasing the thermal conductivity of the structure improved both the forward and reverse actuation processes. When placed in a heated environment, the embedded ethanol vaporized and deformed the structure.

While vapor pressure at a certain temperature considers the equilibrium condition, the time it takes to approach that equilibrium is also critical. The amount of liquid is important when considering this phase transformation kinetics, since required heat is generally proportional to the mass. This is another reason why a very small amount of liquid is generally embedded when a heater is used to boil the liquid. A previous study bypassed this issue by dispersing the liquid into small droplets through ultrasonic atomization.[8] Very strong ultrasonic waves were applied from the exterior, which propagated through the wall and atomized the embedded liquid. During this process, a small amount of heat was generated at the interface between the wall of the structure and the ultrasonic transducer. The total surface area of the small droplets was large enough to vaporize the liquid even when below the boiling temperature (*i.e.*, through evaporation). However, this method required applied voltages that were as high as 320 V, and the speed of actuation was still much slower than a conventional pneumatic pump.

Therefore, the objective of this study is to implement a completely different type of atomization method for improving the performance of actuation through vaporization. Vibrating mesh atomization was employed to drastically lower the required power for atomization. In order to increase vaporization rate, a separate heater with a large surface area was installed above the atomizer. Upon powering the system, the atomizer dispersed small droplets into the air, which vaporized as they passed through the heater. The entire system was enclosed inside a soft elastomer to demonstrate actuation during the vaporization process. This study addresses four limitations of actuation through vaporization. First, the system utilizes evaporation, which does not necessitate high temperatures. This is critical, since most heating elements usually require very high current to heat the system to boiling. Second, much faster actuation speed can be attained by vaporizing small droplets as compared to heating bulk liquid. Third, actuation speed is independent of how much liquid is stored inside the system. This allows one to maintain actuation speed and simply exhaust the vapor for rapid actuation reversal. Fourth, the setup of the system enables actuation regardless of how much the structure is tilted. This is important since methods that boil bulk liquid only work when the liquid is in the vicinity of the heater. This paper starts with a concise background of atomization, followed by the fabrication process. Then, actuation performance was analyzed and compared with other existing methods. In the last section, the method was implemented in a bistable gripper to achieve consistent speed during cyclic motions.

Materials and Methods

Atomization methods

Several methods have been developed to atomize liquid into small droplets. These techniques are implemented in various fields and applications. Pressure atomization generates droplets by discharging liquid through a small orifice.[10] If the pressure drop is sufficiently high, the jet of liquid disintegrates into small droplets. This method is widely used in internal combustion engines,[11] where the large surface area of the droplets provides rapid reaction during combustion. Ultrasonic atomization is another technique that generates droplets by applying strong ultrasonic waves onto a layer of liquid.[12] Beyond a certain threshold, the surface of the liquid becomes unstable and disperses small droplets into the air. In the medical field, ultrasonic atomization is implemented in nebulizers for delivering the precise amounts of drugs to the lungs.[13] Last, vibrating mesh atomization utilizes a mesh to reduce the required power for achieving atomization. Instead of subjecting the liquid itself to ultrasonic waves, this method places a mesh on the surface of the liquid. When this mesh vibrates, the liquid is separated into small droplets as it escapes the small holes of the mesh.[14] In general, this mesh is bonded at the center of a piezoelectric ring to generate such vibrations. Most applications for these atomizers take advantage of the large surface area of the droplets (*e.g.*, faster vaporization). In this study, the vibrating mesh atomizer was used for dispersing droplets into the chamber of a soft elastomer and for their low power consumption.

Fabrication

The setup of the system comprises an atomizer and a heater, which is illustrated in Fig. 1. The piezoelectric ring with the metal mesh was fixed in place above a piece of cotton. The purpose of the cotton is to absorb liquid so that the bottom of the mesh is always in contact with the liquid. When the ring vibrates, liquid stored in the moist cotton escapes through the mesh, and small droplets are dispersed into the chamber. Considering that the vapor pressure of ethanol is already in equilibrium in the sealed system, a separate heater is required to evaporate the droplets. To provide the driving force for evaporation, a heater was installed above the atomizer. The heater's cross-section and surface area was designed to maximize exposure of the ejected liquid droplets to heat. Both the heater and the atomizer were powered simultaneously during actuation. When actuation was tested with a single flat heater, the actuation speed was considerably slower. The heater consisted of interwoven nichrome wires that were sealed between two heat resistant silicone tapes.

The actuator setup was then sealed inside a soft elastomer to inflate the system upon vaporization. The molds for the bottom chamber and the bellows structure were 3D-printed with polylactic acid (PLA). Uncured Dragon Skin FX-Pro was poured into the mold to fabricate the stretchable structures. A tube was connected to the side of the structure to inject liquid into the system initially, as well as for exhausting the vapor after actuation. Since most elastomers have considerable permeability,[3] completely sealing the structure requires periodic injections of the liquid with a syringe. Connecting a tube provided a much easier method to fill the liquid for continued use. Here, 3 mL of ethanol was used as the phase-changing liquid due to its low boiling temperature and chemical inertness.

The image of the 3D-printed holder and the piezoelectric ring is shown in Fig. 2(a). The diameter of the disc was ~ 15 mm, and the inset shows the image of the mesh. The holes were in the shape of a cone with a bottom diameter (reservoir side) of ~ 60 μm and top diameter (dispersing side) of ~ 10 μm. The generated droplets were expected to be in the similar micrometer scale,[15-18] and these droplets were reported to evaporate almost immediately as compared to the actuation time.[19, 20] The atomizer, which was capable of atomizing ~ 11 mg/s in an open system, was then installed inside of a hollow cuboid chamber. One side of the cuboid wall was fabricated with transparent polydimethylsiloxane (PDMS) to visualize the atomization process. The cotton under the mesh was wide enough to cover the walls of the inner chamber. The atomization circuit was powered with 5 V, and the piezoelectric ring was excited with a frequency of ~ 110 kHz. The power consumption of the atomizer was ~ 2 W. Fig. 2(c) shows the atomizer dispersing ethanol into small droplets. The wide area of cotton was capable of absorbing ethanol even when the system was rotated. Consistent atomization is shown in Fig. 2(d), where the system was tilted to one side (Supplementary Video S1).

Results and Discussion

Characterizing actuation

The final structure was placed in front of a grid with gridlines separated by 5 mm, as shown in Fig. 2(e). The atomizer and the heater were powered simultaneously, where the atomizer was powered with ~ 2 W, and 8 V was applied to the heater. The power that was consumed by the heater was ~ 15 W (*i.e.*, current was ~ 1.8 A). The structure started to inflate immediately, and the displacement of the top layer reached ~ 13 mm (strain of ~ 40 %) after 8 s. The inflated structure after actuation is shown in Fig. 2(f). Video (Supplementary Video S2) was recorded throughout the actuation process, and the displacement was periodically measured using image processing. The displacement time history is plotted in Fig. 3(a). Three different voltage conditions (4, 6, and 8 V) were applied to the heater to characterize actuation performance, and these tests were repeated five times to obtain statistically representative results. For all three conditions, Fig. 3(a) shows that the instantaneous displacement (*i.e.*, slope at any given time) stared to decrease with continued actuation, since more force was required to deform the hyperelastic bellows structure.

Blocking stress was also measured by fixing a load cell above the bellows structure, thus fixing the displacement at its initial position throughout actuation. The dotted plots in Fig. 3(b) show the blocking stress for the same voltage conditions, which were also tested five times to calculate the average. The blocking stress reached ~ 1,000 Pa after applying 8 V to the heater for 8 s. Unlike the displacement time histories, the instantaneous slopes in Fig. 3(b) continued to increase, as blocking stress was not affected by the deformed structure. Thus, blocking stress was a better comparison with the temperature increase of the heater. To make such a comparison, temperature change was measured by installing a thermocouple inside the heater. The increasing trend of temperature agreed with the increase in blocking stress. It is worth pointing out that the maximum temperature throughout the test was only ~ 34 °C, which is well below the boiling temperature of ethanol (78 °C). However, applying 8 V to the heater without atomization increased the temperature to ~ 100 °C after 8 s. When the heater was turned on together with the atomizer, the temperature rise was much lower, since the droplets absorbed most of the heat during vaporization.

In order to demonstrate the effects of atomization, a similar test was conducted by submerging the heater under the same amount of ethanol (3 mL). Even after operating the heater with 8 V for 8 s, no change in displacement was observed. Compared to other studies that heat the system beyond the boiling point, implementing atomization provides significant benefits by drastically enhancing actuation speed with significantly less input power. Two parameters can be adjusted to further increase blocking stress. Since stress is directly affected by temperature, simply powering the heater for a longer time or applying higher current will result in higher blocking stress. As mentioned earlier, it was observed that the surface area of the heater highly affects vaporization rate as well. Designing a heater that increases the surface area is also expected to increase blocking stress.

When comparing this work with other methods, the displacement plot in Fig. 3(a) is not a suitable reference. Thus, the displacement was converted to the amount of gas that was generated during actuation. A finite element model (FEM) was used to correlate displacements with volume. The FEM was similar to a method that was introduced in a previous study that used the same material.[21] The bellows structure was modeled as a hyperelastic structure, and the Neo-Hookean parameter was obtained from tensile testing. Then the structure was inflated through the ideal gas model using the following equation.

$$\frac{P}{P_0} = \left(\frac{V_0}{V}\right)^{\gamma} \tag{1}$$

where P is pressure, V is volume, γ is specific heat ratio, and subscript 0 denotes the initial condition. The bellows structure was predominantly discretized with tetrahedron elements, while the bottom layer was fixed in place. The number of elements were ~ 17,000, and the displacement of the top layer was analyzed while increasing gas volume inside the bellows structure. The simulation was used to convert displacement to the corresponding change in volume.

The results of the change in volume are plotted in Fig. 4. To provide a better comparison, the total consumed power is indicated instead of voltage. The applied power of 6, 11, and 17 W corresponds to inputs of 4, 6, and 8 V, respectively. For all three conditions, 2 W was consumed by the atomizer, while the rest was applied to the heater. When 8 V was applied to the heater, vapor was generated at a rate of ~ 2 cm^3/s. It is worth mentioning again that heating the bulk liquid with the same heater showed no change in volume. The results from actuation through ultrasonic atomization[21] are also plotted for comparison. Not only did ultrasonic atomization required higher power (~ 23 W), but its vaporization rate was also significantly lower. In addition, the results were compared with a commercial pneumatic pump. The same structure was connected to a pump with a power consumption of 5 W. The structure was inflated using the pump for 8 s, and displacement was converted into change in volume using results from the FEM. This test was also repeated five times to obtain the average. The analysis showed that the amount of injected gas inside the structure was similar to applying 17 W of power to vaporize ethanol through mesh atomization. Although the technique introduced in this study consumes more power, the result shows promising potential for liquid vaporization to demonstrate comparable performance as when pneumatic pumps are used. Overall, the developed method drastically improved actuation performance (as compared to simple boiling) by adding a vibrating mesh (~ 0.9 g) and a circuit (~ 7.2 g) to control atomization. These additional components are much smaller and lighter versus traditional pneumatic pumps (~ 100 g), which make them suitable for use in untethered and portable soft robotic systems.

Cyclic actuation

The repeatability of actuation through mesh atomization was studied by inflating the structure and exhausting the vapor through a valve. While any type of valve can be implemented, Arduino was used to control a small solenoid valve in this study. One of the benefits of vaporizing liquid through mesh atomization is that it enhances the vaporization rate regardless of how much liquid is stored in the system. This sufficient reservoir of ethanol allows the implementation of valves for the reversing process. The total number of actuation cycles for a fixed amount of embedded fluid can be estimated by assuming the ideal gas condition. The ethanol molar mass of 46.07 g/mol, density of 789 kg/m^3, and molar volume of 22.4 L were used to calculate the number of possible actuations when the change in volume during actuation was ~ 9.4 cm^3. It was estimated that 3 mL of ethanol was capable of actuating the structure ~ 120 times.

The actual experiment was conducted by applying 7 V to the heater during ~ 10 s of actuation, followed by exhausting the vapor through the solenoid valve. The next actuation was performed after 15 s for allowing time for the system to cool. The repeatability of actuation is plotted in Fig. 5. The minimum and maximum temperature during cyclic actuation testing is also overlaid as an area plot. The inset shows a zoomed-in portion of the time history response to better visualize its displacement and temperature response. The maximum displacement slowly increased, since temperature did not reach the initial value after each cycle. Although 3 mL of ethanol was estimated to actuate the structure for ~ 120 times, the maximum displacement started to decrease after ~ 50 times. The most critical reason for this large discrepancy was because the chamber was completely filled with droplets during actuation. When opening the valve, a small portion of these droplets also escaped in addition to evaporated ethanol gas. Furthermore, the fact that the chamber was filled with the droplets also indicated that the atomizer was generating more droplets than the heater could evaporate. Thus, reducing the atomization rate is expected to minimize the escaping droplets and increase the number of consistent actuation cycles. The decreasing maximum displacement after ~ 50 cycles also indicates that a certain amount of ethanol is required for the liquid to be fully in contact with the vibrating mesh and for it to atomize properly. Atomization rate rapidly decreases when the remaining ethanol was less than this required amount. This can also be observed from the temperature increase after ~ 50 cycles of actuation due to less heat absorbed during phase transformation. Nevertheless, the current test setup was capable of actuating the structure for ~ 50 times using only 3 mL of ethanol.

Portable bistable gripper

Compliant mechanisms are widely used to convert the direction of movement,[22] amplify or reduce the degree of stress and strain,[23] and perform rapid movements through buckling.[24] Since cooling takes much longer than actuation for methods involving phase change, a bistable structure with a built-in snap-through buckling mechanism was utilized to achieve consistent movement speed. In addition, the bistable buckling mechanism can be used to maintain displacement without the need to consistently power the actuator. The schematic of the bistable gripper is shown in Fig. 6(a). The bistable finger was 3D-printed with thermoplastic polyurethane (TPU), and the stiff outer structure was 3D-printed with PLA. Two inflating structures were fixed in place to activate the buckling of the finger. Valves were not implemented for this demonstration, since buckling provides fast and consistent speed during the back-and-forth movements.

The amount of load that is required to activate buckling and bistable response was analyzed for characterizing the actuation process. Fig. 6(b) shows a simplified drawing of the buckling structure, where the length between points A and B (d_{AB}) is the same as the length between points A and C (d_{AC}). The required force at point A is expected to vary throughout the deformation process. The force that spreads points B and C (F_{BC}) can be expressed as follows:

$$F_{BC} = \frac{F \sin\theta}{2\cos\theta} \tag{2}$$

where F is the vertical force applied at point A, and θ is half of the angle ∠BAC. Since the required F_{BC} increases as the distance between B and C (d_{BC}) increases, F_{BC} can be expressed as a function of Δd_{BC}. When Δd_{BC} is small, the relationship can be assumed to be linear.

$$F_{BC} = E \times \Delta d_{BC} \tag{3}$$

where E is a proportionality constant or an equivalent stiffness of the system. This relationship was measured by spreading points B and C with a universal tensile machine (UTM), and the measured value for E was 2.91 N/mm. Here, Δd_{BC} can be expressed as follows from Fig. 6(b).

$$\Delta d_{BC} = 2d_{AB}(\sin\theta - \sin\theta_0) \tag{4}$$

where θ_0 is the initial angle. Combining equations (2), (3), and (4) results in:

$$F = 4Ed_{AB}\frac{\cos\theta}{\sin\theta}(\sin\theta - \sin\theta_0) \tag{5}$$

The initial angle (θ_0) was 74°, and d_{AB} was 26 mm for the fabricated gripper. The predicted F was compared with experimental results to analyze the actuation process.

The image of the fabricated gripper is shown in Fig. 7. The portable system consisted of two lithium polymer (LiPo) batteries, a 9 V battery, a circuit for the atomizer, and a double-pole double-throw (DPDT) toggle switch. The two LiPo batteries were connected in series, and the output voltage was ~ 8 V when fully charged. These LiPo batteries were used to power the heater, and the 9 V battery was used to power the atomizer. Actuating the two inflating structures in sequence demonstrated cyclic motion of the bistable structure. Similar to the displacement measurements conducted earlier, video was recorded, and image processing was used to determine the distance between the two fingertips (Supplementary Video S3).

Before actuating the structure, the UTM was used to buckle the finger by vertically pressing down at point A. The dotted plot in Fig. 8(a) shows the experimental results, and the plot is compared with the analytical prediction. The two results were in fairly good agreement. The required load increased and reached a maximum value of ~ 1.2 N when displacement was ~ 3 mm. After reaching the maximum point, the load started to decrease until the finger buckled after ~ 7 mm of vertical displacement. The first region with increasing load was labeled as I, and the second region with decreasing load was labeled as II. It can be predicted that the finger will move much faster once it reaches region II, since the required load decreases.

The distance between the two fingertips during actuation is plotted in Fig. 8(b). When the upper actuator was turned on (at 0 s), the fingertip started to move slowly (region I). Its speed continued to increase, and the fingertip moved much faster as it reached region II. It was clearly observed that region I took much longer than region II, and this can be explained by the reducing load requirement in region II. Once the fingertip reached the critical buckling point, the finger snapped through and moved to the other end. By implementing the proposed actuator, the finger was actuated within 10 s of actuation, while boiling is expected to take several minutes. After the first actuation at ~ 8 s, the system was turned off for a short amount of time. Actuating the lower inflatable structure at ~ 14 s showed a similar result and returned the fingertip to its original position. Fig. 8(c) shows the images of the fingertips for each region. It is worth pointing out that the final distance was slightly smaller than the initial distance. This is because the first upper inflatable structure did not fully cool down after the second actuation sequence. Nonetheless, the two actuation speeds were quite consistent, which shows the potential of implementing bistable structures to overcome the dissimilar speed between heating and cooling the system when actuated by vaporization.

Conclusions

This paper introduces the very first implementation of vibrating mesh atomization in soft actuation systems. This novel method of rapidly vaporizing liquid inside a soft elastomer is promising for replacing pneumatic pumps. The small actuator consisted of a metal mesh, piezoelectric ring, piece of cotton, and heater. The purpose of the cotton was to absorb the embedded liquid and allows the mesh to be in contact with the liquid regardless of the actuator's physical orientation. When the piezoelectric ring vibrated the metal mesh, liquid was dispersed into small droplets. The heater was designed to maximize surface area, which directly affected vaporization rate. Overall, the proposed method provides several advantages with respect to conventional actuation methods (*i.e.*, boiling bulk liquid for actuation) in several aspects. First, dispersing the liquid into droplets opens the possibility of implementing evaporation instead of boiling. The results showed that considerable actuation was achieved even at temperatures well below boiling. Second, the vaporization rate of the proposed method was much higher as compared to using the same heater for boiling the same amount of liquid. Third, actuation through vibrating mesh atomization could maintain a high vaporization rate even when a large amount of liquid is stored in the system. This allowed utilizing valves to simply exhaust the vapor rather than slowly cooling the system when trying to reverse the actuator's motions. Fourth, actuation was still functional even when the system was tilted. This was also an improvement as compared to boiling bulk liquid with a heating element, since the liquid would no longer be required to be in contact with the heater in this case. In addition, although the required power of the introduced method was ~ 3 times higher than a commercial pneumatic pump, the gas generation rate was almost similar. This is a great improvement, because a small piezoelectric ring and a heater can potentially replace heavy and bulky pumps.

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Author Disclosure Statements

The authors declare no competing financial interests.

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