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An overview of solid-state pumps for industrial use

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Abstract
In this study, research has been made on the production, working principle and materials of a hydraulic pump, which is environmentally friendly, cheaper than other hydraulic pumps, and uses piezoelectric actuators despite increasing environmental pollution. It has been seen that it is well ahead of its competitors in terms of weight, volume and energy.

Introduction

According to recent research, there is a serious increase in environmental pollution. For this reason, it is extremely important for most companies that directly or indirectly interact with the environment to investigate the impact of the materials they produce on the environment. Studies to reduce carbon emissions are also based on this awareness. This is the main reason why companies adopt the philosophy of doing more with less energy. Due to these considerations, actuators made of solid state electroactive smart materials, which are expected to work even more efficiently, have been intensively studied. These smart material actuators have a positive impact on most industries that use aerospace and hydraulic based materials, starting with the biomedical fields.

Although it has many advantages, it is foreseen that it will be very useful due to its flexibility, strength as well as lightness and also simple working mechanisms. They have the potential to operate without noise and vibration with low power consumption. It is also possible to enlarge or reduce in size. The production methods are quite simple. They are also easily integrated into other devices.

Research on solid state pumps has been conducted in the last 20 years. Solid state pumps produce a pressure of 180 bar with very little energy consumption such as 24 V. Although the output pressure is lower than other pumps, if we compare the efficiency, it makes a serious difference compared to its competitors. In addition, a pump with this efficiency weighs only 0.73 kg. For this reason, if used, it will provide extremely important advantages compared to the vehicle in which it is used. In particular, since the weight will be reduced, it will reduce fuel consumption and significantly reduce the carbon emissions released into the air. For all these reasons, it is possible to say that solid state pumps are extremely environmentally friendly [1]. Said hydraulic pump is shown in Figure 1.

Figure 1. Solid State Pump [1]

Material and Method

Solid state pumps use piezomotors as energy source. These motors convert electrical energy into mechanical energy with the help of piezoelectric effect. The piezoelectric effect, which we can easily see on these motors, especially on magneto lighters, gives incredibly efficient results, especially in minimal sized mechanisms. Although the principle is the same, in the lighter system, mechanical energy is converted into electrical energy [2]. The mentioned mechanism is clearly seen in Figure 2.

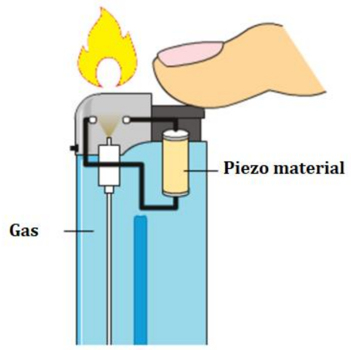

Figure 2. Magneto Lighter [2]

During the expansion stroke, the actuator pressurizes the pump chamber using part of its stroke to tolerate fluid mismatches. The actuator expands by pumping fluid through the dispense valve towards the outlet side. Just before it intersects the load line, the actuator only performs about half of the free kick. The actuator then goes into the retracting state, causing the pressure in the pumping chamber to drop. Afterwards, it allows the liquid to enter the pumping chamber through the inlet valve and the desired pressure value is obtained. Finally, unloading of the actuator takes place, which causes the displacement to return to its starting point. Then, the actuator is energized for cycle repetition [3]. During all these events, as a result of the back-and-forth movement of the actuator located in the middle of the system, fluid absorption is realized. The absorbed liquid is pumped at high pressure as a result of the compression of the engine. Therefore, the desired pressure levels are easily reached. The mentioned cycle event is clearly seen in Figure 3.

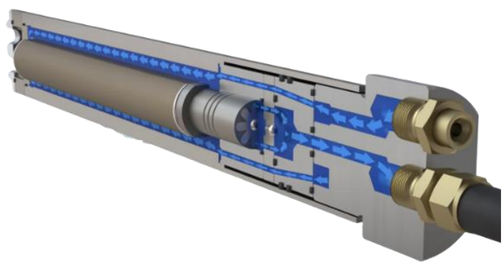

Figure 3. Solid State Pump Cycle [1]

Piezomotors, which are used as power sources in solid state pumps, are a device that can be used for various precision applications in many different fields. The main purpose of piezomotors is to produce motion based on small deformations of a material when an electric current is applied [4-5]. Piezomotors convert electrical energy into mechanical energy by using the magnetic movements of the piezolegs. Piezobes need to create a magnetic field against the electric current. Therefore, the materials of the piezolegs are very important. Its main materials are ceramics consisting of Lead Zirconate Titanate, Quartz, Tourmaline Barium Titanate, Zinc Oxide, Polyvinylidene chloride. The most preferred material is Lead Zirconate Titanate. It is possible to process these ceramics, which are in powder form and in certain shapes, to bring them into relevant shapes. The virtual model of piezolegs is shown in Figure 4.

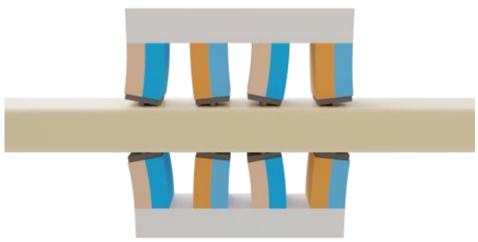

Figure 4. Piezolegs [6]

Actuators to be preferred for using pumps can be composed of composite materials or smart materials. In addition, the material may differ in shape and dimensions. The strain produced by their parties can affect the volumes they pump per revolution and their stress, as well as the pressure heights. The work done on the unit weight of the liquid transferred from the inlet to the outlet on the pump is called pressure. Actuators, which are the main parts of pumps, directly affect the pump performance due to their excitation voltages (U), frequencies (f) and the fluids they operate. The main characterization of pumps is their performance. Solid state pumps, on the other hand, give very good results compared to their competitors when considered in terms of performance/efficiency.

Smart Materials Actuator Used in Solid State Pumps

Solid state pumps using smart materials are differentiated according to smart material actuators driving the pumps. To date, unidirectional shape memory alloy (U-SMA), piezoelectric ceramic (PEC), dielectric elastomer (DE), ferroelectric polymer (FEP), ionic polymer metal composite (IPMC) and conductive polymer (CP) based actuators are used.

U-SMA (Unidirectional Shape Memory Alloy) Actuators

U-SMA actuators consist of (Ni)-(Ti) alloys. These actuators exhibit unidirectional shrinkage when transitioning from the low-temperature martensitic phase to the high-temperature austenitic phase. U-SMA actuators are adaptable to sheet, wire and springs. These may be biased to induce bidirectional movements.

However, U-SMA unimorphs can also be used, which exhibit bidirectional unidirectional bending without the need for greater prestressing. U-SMAs require voltages around 5 V and their full duty cycle can be limited to low operating frequencies as they require passive restoration to cool from high temperature austenite phases to low temperature martensite phases. However, these times can be reduced by active cooling or by using films that have a large surface-to-volume ratio and can therefore dissipate heat quickly. The latter can operate at frequencies up to 100 Hz [7].

PEC (Piezoelectric Ceramic) Actuators

Zinc oxide (ZnO) and lead zirconate titanate (PZT) crystals are common smart materials. Gold (Au), chrome (Cr), platinum (Pt) etc. metal electrodes can be applied to PECs. PECs contain fields with electric dipoles of similar orientation. Due to the piezoelectric effect, in voltage applications, the smart material expands when the direction of the electric field is opposite to the polarity of the retained electric dipoles when the voltages are removed. When it is reversed, it contracts. PEC actuators can be discs, rings, plates, or single crystals with electrodes formed as sheets. Lightweight piezo-composite curved actuators (LIPCAs) are uniform structures produced by bonding a pre-stressed PEC layer electroded on one side to a fiber-reinforced epoxy layer on the other side to generate high forces and displacements [9]. PECs cause voltages greater than 100 MPa and can have extremely high bandwidths of up to 10 MHz. Hard rated PZTs generate extremely small voltages of 0.1% for excitation voltages in the kV range. Soft PZTs exhibit 2-10% strains up to 150 V [8-9].

DE (Dielectric Elastomer) Actuators

DE actuators are three layers with electrodes such as PDMS, Silastic or NuSil or acrylic like film. Dielectric membranes are generally prestressed to obtain optimum operating properties; therefore, axial constraints are necessary. Conventional electrodes for DEs are graphite or carbon (C) based. When the electrodes of the DE are positively and negatively charged due to Coulomb forces by applying a voltage difference, the DEs expand unidirectionally in the plane. Smart materials relax to their original state when voltages are removed [10]. DE actuators may consist of a single film or multiple films stacked or wound together [11]. DEs require high voltages for operation in the 100 kV range (close to the dielectric breaking strength of polymers). Bandwidth is high for silicon-based DEs, 1400 Hz and 10 Hz for VHB-based. Working stresses are up to 5 MPa and strains are typically 10-30% [12]. However, DEs can also exhibit large deformation of the order of ε = 1.692 % due to electromechanical instability or the 'transition' phenomenon [13] that occurs under a combination of electro-mechanical loadings [14]. This was initially reported to be an irreversible process [13], but has recently been shown to be reversible [15,16].

FEP (Ferroelectric Polymer) Actuators

The most common types of FEP are polyvinylidene fluoride (PVDF or PVF2) - trifluoroethylene (TrFE) copolymers. Relaxor FEP loses its advanced properties due to defects in its structure. These can be induced by pre-stretching, irradiation with electrons, or combining the two techniques. The applied electrodes are usually metals such as Al, Cr or Au. Ferroelectric is a type of piezoelectric. P(VDF-TrFE) exhibits bidirectional expansion and contraction when voltage is applied. P(VDF-TrFE) FEPs are generally single layer actuators or membranes that can be used as stacked. They can also be included in unimorphs. P(VDF-TrFE) actuators require high electric fields of 150 MV/mand voltages > 1 kV for voltages of 3.5-7%. They also exhibit high voltages up to 45 MPa and can operate in a wide frequency range up to 100 Hz [7].

IPMC (Ionic Polymer Metal Composite) Actuators

IPMC actuators are three layers, mostly consisting of a Nafion ionomer and two Pt electrodes on both sides. IPMCs based on the former produce large forces and fast responses, and those based on the latter produce large deformations and slow responses. IPMCs generally work in water, but they can also work with liquid salts as dehydration can occur and adversely affect their starting properties. When voltage is applied to water-powered Nafion-based IPMCs, the actuators exhibit bidirectional bending upon a change of polarity of the applied voltage due to migration of hydrated ions. IPMCs are typically based on single membranes of Nafion. They are usually consoles, but they can also be fixed perimetrically, bulging when operated [17-21].

CP (Conductive Polymer) Actuators

CP actuators consist of a CP called a working electrode, a counter electrode, which is usually also a CP, and an electrolyte, which can be solid or liquid. The most common example of CP is Polypyrrole (PPy). When voltage is applied to these actuators, the CPs exhibit bidirectional activation. CP actuators are generally film-based and uniform actuators are most common. PPy actuators require 2–35% voltage and 1–3 V undervoltage for voltages up to 34 MPa. Also, frequency responses can reach several Hz [20,21].

Conclusion

As a result of the researches, solid state pumps that can produce pressure values close to the same levels by using less energy consumed by existing hydraulic pumps have been examined. When the efficiency comparison is made, it is concluded that its use will be more advantageous in terms of both energy consumption and volume. In the tests carried out, certain pressures were reached. It has been observed that even if the pressures reached are not at very high levels, they can be used up to 180 bar. It is clearly seen that it will provide many advantages in terms of energy and weight savings, especially if it is used in hydraulic circuits where there is no need for very high pressure. In addition, due to all these reasons, it will reduce fuel consumption and thus contribute significantly to reducing carbon emissions.

References

1. Kinetic Seramics, Solid State Pump (2010s). Retrieved from https://www.kineticceramics.com/products/solid-state-pumps/
2. Yerelbt, (2015). Piezoelektrik/Manyetolu çakmak nasıl çalışır? Retrieved from https://www.yerelbt.com/tag/manyetolu-cakmak-nasil-calisir/
3. O'Neill, C., & Burchfield, J. (2007, April). Kinetic ceramics piezoelectric hydraulic pumps. In *Industrial and Commercial Applications of Smart Structures Technologies 2007* (Vol. 6527, pp. 142-155). SPIE.
4. APC International Ltd., (2020). What is the purpose of a piezo motor? Retrieved from https://www.americanpiezo.com/blog/what-is-the-purpose-of-a-piezo-motor/
5. MalzemeBilimi.net, (2015). Piezoelektrik Malzemeler ve Nanojeneratörler. Retrieved from https://malzemebilimi.net/piezoelektrik-ve-malzemeler-ve-nanojeneratorler.html
6. PiezoMotor, (2019). Piezo LEGS Technology. Retrieved from https://piezomotor.com/this-is-a-test/
7. Madden, J. D., Vandesteeg, N. A., Anquetil, P. A., Madden, P. G., Takshi, A., Pytel, R. Z., ... & Hunter, I. W. (2004). Artificial muscle technology: physical principles and naval prospects. *IEEE Journal of oceanic engineering*, *29*(3), 706-728.
8. King, T. G., Preston, M. E., Murphy, B. J. M., & Cannell, D. S. (1990). Piezoelectric ceramic actuators: A review of machinery applications. *Precision Engineering*, *12*(3), 131-136.
9. Yoon, K. J., Shin, S., Park, H. C., & Goo, N. S. (2002). Design and manufacture of a lightweight piezo-composite curved actuator. *Smart Materials and Structures*, *11*(1), 163.
10. Madden, J. D., Carpi, F., De Rossi, D., Kornbluh, R., Pelrine, R., & Sommer-Larsen, P. (2009). Dielectric elastomers as high-performance electroactive polymers. *Dielectric Elastomers as Electromechanical Transducers: Fundamentals, Materials, Devices, Models and Applications of an Emerging Electroactive Polymer Technology, F. Carpi, et al., Eds., ed: Elsevier*.

11. Kornbluh, R., Carpi, F., De Rossi, D., Pelrine, R., & Sommer-Larsen, P. (2008). Fundamental configurations for dielectric elastomer actuators. *Dielectric elastomers as electromechanical transducers: Fundamentals, materials, devices, models and applications of an emerging electroactive polymer technology*.
12. Pelrine, R. E., Kornbluh, R. D., & Joseph, J. P. (1998). Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation. *Sensors and Actuators A: Physical*, *64*(1), 77-85.
13. Keplinger, C., Li, T., Baumgartner, R., Suo, Z., & Bauer, S. (2012). Harnessing snap-through instability in soft dielectrics to achieve giant voltage-triggered deformation. *Soft Matter*, *8*(2), 285-288.
14. Goulbourne, N., Frecker, M. I., Mockensturm, E. M., & Snyder, A. J. (2003, July). Modeling of a dielectric elastomer diaphragm for a prosthetic blood pump. In *Smart structures and materials 2003: Electroactive polymer actuators and devices (EAPAD)* (Vol. 5051, pp. 319-331). SPIE.
15. Li, Z., Wang, Y., Foo, C. C., Godaba, H., Zhu, J., & Yap, C. H. (2017). The mechanism for large-volume fluid pumping via reversible snap-through of dielectric elastomer. *Journal of Applied Physics*, *122*(8), 084503.
16. Ho, S., Banerjee, H., Foo, Y. Y., Godaba, H., Aye, W. M. M., Zhu, J., & Yap, C. H. (2017). Experimental characterization of a dielectric elastomer fluid pump and optimizing performance via composite materials. *Journal of Intelligent Material Systems and Structures*, *28*(20), 3054-3065.
17. Wang, J., McDaid, A., Sharma, R., Yu, W., & Aw, K. C. (2015). Miniature pump with ionic polymer metal composite actuator for drug delivery. Royal Society of Chemistry
18. Shahinpoor, M. (2015). Fundamentals of ionic polymer metal composites (IPMCs). Royal Society of Chemistry.
19. Shahinpoor, M. (2015). Ionic polymer metal composites (IPMCs) optimal manufacturing. Royal Society of Chemistry.
20. Madden, J. D. (2007). Polypyrrole actuators: Properties and initial applications. In *Electroactive Polymers for Robotic Applications* (pp. 121-152). Springer, London.
21. Sideris, E. A., & de Lange, H. C. (2020). Pumps operated by solid-state electromechanical smart material actuators-A review. *Sensors and Actuators A: Physical*, *307*, 111915.