Use of Piezoelectric Technology for Fluid Valves as an Energy Saving Alternative

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***Abstract**. Fluid control valves are an integral part of production equipment. With the development of new technologies such as piezoelectric actuators, new control possibilities are opening up. Piezoelectric actuators are characterized by low power consumption and noise with very fast and precise movement. In light of the new machine building philosophies of Industry 4.0, machine building components must be more versatile and consume less energy. The standard technology of so-called solenoid valve types is limiting in its design, operating principle and power consumption. Piezoelectric actuators offer wider valve control possibilities and have lower energy consumption. This paper describes the piezoelectric phenomenon itself, piezoelectric materials and their properties, actuators and the possibility of using them in fluidic control valves, indicating their main advantages over conventional valves.*

Keywords. piezoelectric phenomenon, piezoelectric materials, piezoelectric drives, fluid control valves, energy consumption

1 Piezoelectric Phenomenon and its Properties

The piezoelectric phenomenon was discovered and confirmed by the brothers Pierre and Jacques Curie in 1880 in experiments with materials such as Siegnett's salt or tourmaline. The basis of this phenomenon is the ability of so-called piezoelectric materials to electrically polarize - to generate an electric charge - when stressed by pressure, tension, bending, or twisting. Experiments have confirmed both the direct piezoelectric phenomenon and the indirect (inverse) piezoelectric phenomenon.

In direct piezoelectric phenomenon, the mechanical stress on the piezoelectric material results in the displacement of ions in the crystals of piezoelectric materials, resulting in the generation of an electric charge. This property of piezoelectric materials is used in practice to sense physical values such as pressure and deformations, or to provide energy for various devices in automation or biomedicine. "Over the past few decades, the functionality of energy harvesters based on piezoelectric energy from mechanical vibrations has been extensively investigated in energy technologies. In the case of low power electronic devices, energy harvesting is generally in the mW or μW range. In addition, the majority of these applications involve equipment that has the ability to operate both indoors and outdoors in such a way that it does not have a significant dependence on climatic conditions. Energy harvesting is a promising area that enables Internet of Things (IoT) devices to generate electricity by absorbing energy from the environment" (Bobic et al.2023).

The indirect (inverse) piezoelectric phenomenon manifests itself as a deformation of the piezoelectric material that occurs on the crystals when they are connected to an electric voltage or when they are placed in an electric field. This phenomenon is used in practice as a drive for precise and fast positioning such as focusing camera lenses. The use of the indirect piezoelectric phenomenon has also been elaborated and used to actuate fluidic valves. It can also be used to produce sound and ultrasound generators (Tamburrano et al., 2020).

The generation of charge on the surface of crystals, or the deformation of the material when a voltage is applied to the material, is called the piezoelectric properties of the material. Piezoelectric properties can be seen on acentric crystals, crystals without central symmetry. Therefore, when deformed in the vertical direction, they change the distance of positive and negative charge. The charges move away from each other and their centres of gravity no longer match - an electric dipole is formed (Fig. 1) (Budkova, 2022), (What is Piezoelectricity? 2024).

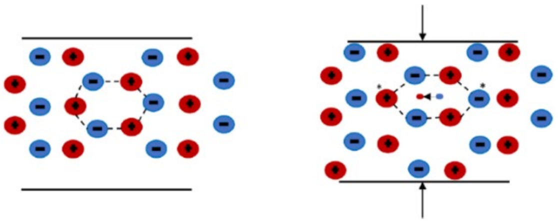

Figure 1. Structure of a piezoelectric material (Budkova, 2022)

The correct function of a piezoelectric material is also influenced by the so-called Curie temperature (Tc). If this temperature is exceeded the material loses its typical piezoelectric properties. At temperatures higher than Tc, piezoelectric materials undergo significant changes in their internal structure - the arrangement of atoms in the crystal lattice is deformed. Grains with a slightly deflected central ion give rise to symmetrical grains in which no electric dipoles are formed and spontaneous polarization of the material occurs (Budkova, 2022).

The size of the piezoelectric phenomenon can be described by piezoelectric constants. Important parameters of piezoelectric materials include:

- Piezoelectric charge constant d_{ij} which gives the magnitude of the generated charge per area with respect to the applied mechanical stress and the area ($C.N^{-1}$). For indirect piezoelectric phenomena, this constant is equal to the mechanical deformation of the area when a voltage is applied ($m.V^{-1}$). This constant is very important in the selection of a suitable material for actuators (Budkova, 2022), (Piezoelectric charge constants, 2024).
- Piezoelectric voltage constant g_{ij} which indicates the magnitude of the electric field generated by the piezoelectric material with respect to the applied mechanical stress. Materials with high voltage constant have large output voltage and are mainly used for sensors (Budkova, 2022), (Piezoelectric charge constants, 2024).

2 Piezoelectric Materials

In order for a material to be labelled as piezoelectric, it must have a specific structure - a non-symmetrical arrangement of elements. The piezoelectric phenomenon is not the same for all materials. Some like natural materials it is very small. For this reason, research has focused on making materials that have a larger piezoelectric effect after modification.

To enhance the properties of the piezoelectric phenomenon, it is necessary for some materials to arrange (polarize) the randomly acentric grains in the crystal structure. The poling is done by placing them in an electric field in which the temperature is raised and the structure is subsequently cooled. The result is a material with permanent piezoelectric properties. It is an electrical reorientation and alignment of electric dipoles (Fig. 2) (Budkova, 2022), (Pinto et al., 2017).

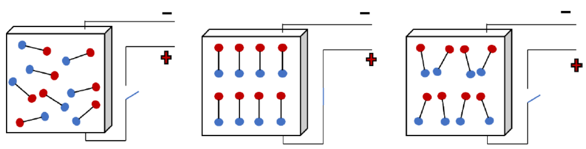

Figure 2. Feroelctrical ceramics before, during and after polarisation (Budkova, 2022)

2.1 Monocrystalline Structures

Materials such as quartz, tourmaline and Siget salt are natural single crystalline materials with an already built-up dipole structure. In the rest state, these materials are electrically neutral. When they are mechanically stressed (squeezed, stretched, twisted, bent), ions are displaced and thus charged - forming an electric dipole. Quartz is one of the best-known natural materials with an asymmetric structure that is alternately composed of positive charges (silicon ions) and negative charges (oxygen ions). Its great advantage is the small dependence of the piezoelectric coefficient on temperature, unlike other crystalline substances, which have non-negligible pyroelectric properties. In addition to this property, the stability of its lower form up to 573°C also predisposes it to work at higher temperatures (Budkova, 2022), (Plass, 2009), (Overview of minerals and rocks, 2024)

2.2 Ceramic Piezoelectric Materials

During the 1950s, new ceramic piezoelectric materials were developed, enabling their use in several applications such as sensors, actuators and piezoelectric motors. These are polycrystalline ceramic materials that are paraelectric in the normal state. They acquire piezoelectric properties only after polarisation in a strong electric field. These ceramic materials include, e.g., barium titanate $BaTiO_3$, lead zirconate $PbZrO_3$ or the most widely used material is the PZT ceramic $Pb(Zr_xTi_{1-x})O_3$ (Plass, 2009).

2.3 Organic Piezoelectric Polymers

The third group of piezoelectric materials are organic piezoelectric polymers, the most widely used are polyvinylidene-fluoride PVDF and difluoro-polyethylene PVF2. They are characterised by a piezoelectric coefficient up to several times higher than quartz crystals. They are used as sensors and most often as sensitive acoustic and vibration sensors. Their production is also considerably simpler than e.g. ceramic piezoelectric materials (Plass, 2009).

3 Piezoelectric Actuators

In industry and especially in scientific fields such as precision machining, precision measurement, biological and genetic engineering, micro/nano positioning systems with micro/nano precision are very important. Actuators refer to functional devices that can perform specific motions such as linear, or rotational motion (Cheng, Li, 2022). Actuators commonly used in industry, such as pneumatic, hydraulic or electric actuators, have the ability to perform longer strokes with greater forces, but have larger size and power consumption, but mainly lower positioning accuracy and speed. For applications that require more precise positioning, high speed and low power consumption, piezoelectric actuators are more efficient. Piezoelectric actuators are characterized by compact size, light weight, high accuracy, fast response, good control characteristics, high energy density, low power consumption, and are free from magnetic field interference (Cheng, Li, 2022).

Based on their working principle, piezoelectric actuators can be divided into direct-driving piezoelectric actuators and stepping piezoelectric actuators. In direct-driving types, the deformation of the piezoelectric element is directly used to move the output mechanism. The working stroke of these actuators is small. Stepping types use a stepping motion mode whereby larger strokes can be realized. For the purpose of controlling pneumatic valves, directly controlled piezoelectric actuators have the best prerequisites, which can be further divided into actuators with and without a amplification mechanism as can be seen in the Fig. 3 (Cheng, Li, 2022).

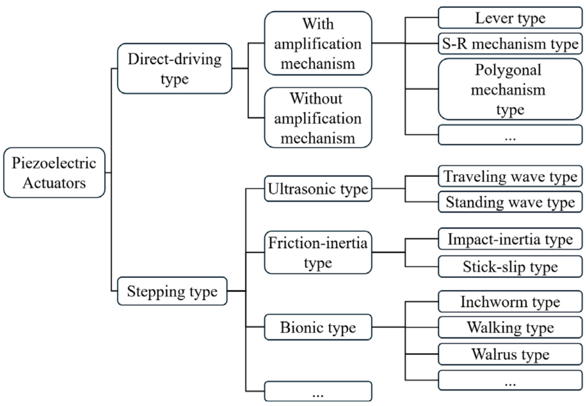

Figure 3. Piezoelectric actuator types (adapted from Cheng, Li, 2022)

4 Piezoelectric Composite Structures

In applications that use direct-driving piezoelectric actuators, piezoelectric materials form single or multilayer structures. From a mechanical point of view it can be either a membrane, a built-in beam fixed on one side (bender), or multilayered microactuators (Budkova, 2022), (Plass, 2009).

4.1 Unimorphic Structure

This structure is made up of a metal plate on which a layer of piezoelectric material is deposited and has power connections (Fig. 4). They are most commonly used in electroacoustic transducers and sensors of non-electrical quantities (Plass, 2009), or in precision small-volume dispensers (Hradil, 2011).

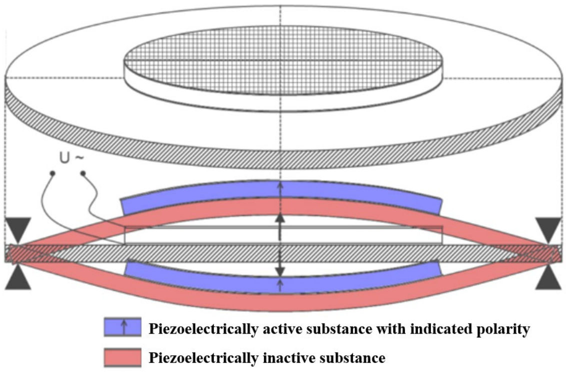

Figure 4. Unimorphic membrane (Hradil, 2011)

4.2 Bimorphic Structure

This type of structure consists of two piezoelectric layers that can be combined with other materials such as thin metallic sheets or plastics. According to the way the voltage is applied, bimorph structures are divided into serial and parallel types. Parallel bimorph structures have twice the deflection (deformation) of serial bimorph structures at the same voltage. In the serial circuit, the supply voltage is applied to the edges of two connected piezoelectric wafers and in the parallel circuit, one pole is connected to a metal electrode sandwiched between two piezoelectric wafers and the other pole is connected to the edges of these wafers (Fig. 5). For bimorphic structures, the stroke is in the range of hundreds to thousands of microns and the bending force in Newtons (Plass, 2009). Bimorphic structures are suitable for the design of bending beams.

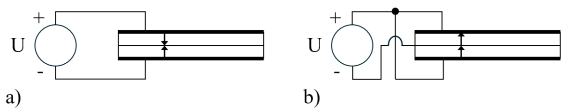

Figure 5. a) Serial bimorphic structure, b) Parallel bimorphic structure (Plass, 2009)

4.3 Polymorphic Structure

These structures consist of more than two piezoelectric layers, thereby increasing efficiency and reducing electrical voltage at the same power. Movement occurs in the direction of the layered piezoelectric elements (Fig. 6). These structures have working deflections in tens of microns and are capable of exerting a force in hundreds up to thousands of Newtons (Plass, 2009). Polymorphic structures are suitable for the design of layered micro actuators.

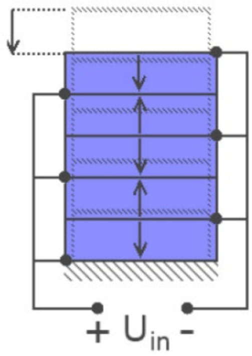

Figure 6. Polymorphic structure (Hradil, 2011)

5 Use of Piezoelectric Actuators to Control Fluidic Valves

Fluidic valves are widely used in all parts of our life. Starting with medical equipment thru daily used gadgets up to the industry. The most used technology because of its versatility is pneumatics (compressed air). If we want to control pneumatical systems we need different types of valves. Directional (way) valves and pressure or flow control valves.

The role of pneumatic way valves is to connect the individual working connections and thus ensure the flow of compressed air to the different parts of the equipment at the specified time. They can be controlled in a number of ways (manually, mechanically, by air, etc.). In modern automation equipment an electrical control is the most used type of actuation. Regardless of the method of actuation, pneumatic valves are divided into directly controlled and indirectly controlled valves.

In directly controlled valves, the force generated by the control is used directly to move the internal parts of the valve. This type of valve requires a control that is capable of generating a higher force, which in the case of solenoid coils means a larger design and therefore a higher power consumption.

In the case of indirectly controlled valves, the force generated by the control does not act directly on the internal parts of the valve, but uses other energy (e.g. compressed air) to increase the actuating force. This type of design allows the use of smaller components (solenoid coils) and thus reduces energy consumption.

All three types of piezoelectric composite structures can be used to control pneumatic control valves, each with its own advantages and disadvantages.

For biomedical applications where the application requires the smallest possible valve size, a diaphragm (unimorphic) type of piezoelectric actuator is ideal. For microfluidic biomedical systems, this type is the most efficient because it has a very simple design (contains a minimum of moving parts) thus significantly reducing the risk of failure (Fig. 7) (Durasiewicz et al., 2021).

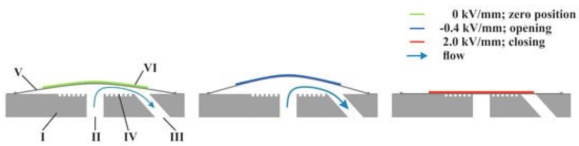

Figure 7. Membrane piezoelectric valve (Durasiewicz et al., 2021)

A different approach is to control a manifold servo valve using a layered piezoelectric micro actuator, i.e. an actuator with a polymorphic structure (Fig. 8). This method of actuation is fast and accurate, but the ratio between the piezoelectric actuator and the way valve itself is not ideal. The piezoelectric actuator does not achieve the working stroke that is directly required to override the way valve. For this reason, it uses a lever mechanism which increases its working stroke but also its design size, making the piezo actuator with the stroke increasing design in this case as large as the body of the way valve itself. Because of the mentioned ratio between actuator and valve size, this principle is not suitable for structurally larger valves, but also not for small valves or micro-valves used in biomedical applications. It can be used in applications where the size of the actuator is not required (Park et al., 2021).

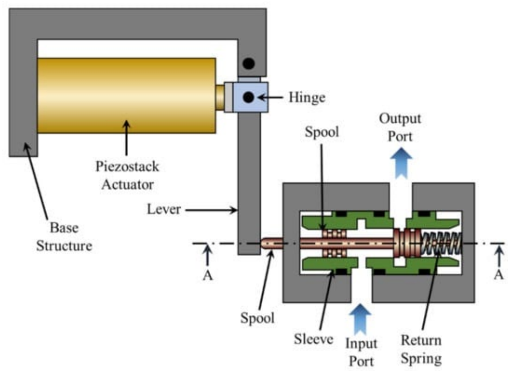

Figure 8. Way valve with piezostack actuator (Park et al., 2021)

If the application requires flow or pressure control, proportional valves (servo valves) must be used. For these types of valves, the bending-beam design (Fig. 9) is best suited. Compared to proportional solenoid valves, it has up to 95% lower power consumption (depending on the valve construction), is noiseless and does not generate heat (Easy integration of piezo valves for gas handling, 2021). The energy consumption is ensured by the fact that after polarization of the piezo valve, it remains in the position to which it was set even after the power supply is disconnected. By not having to constantly power the valve a very large amount of energy is saved. Although up to 310V is required to operate these valves, the corresponding current is very small (max. 5 mA) (Valves with piezotechnology, 2018).

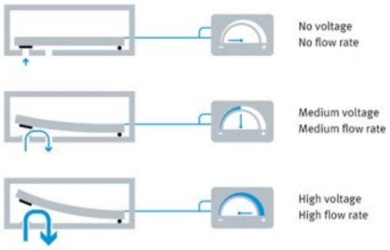

Figure 9. Proportional valve with bending beam actuator (Valves with piezotechnology, 2018)

For applications with higher flow requirements, this technology can also be applied to indirectly controlled valves.

6 Comparison of Power Consumption of Proportional Valves

Market offers a wide range of proportional valves with different constructions. The aim for the machine builders is to use a valve with low power consumption so they can reduce the operating costs for their machines thus reducing operating costs and ensuring sustainable production. Power consumption of a proportional valve depends on its construction of the control circuit, so called pilot stage. The main working stage is in this case not important, because it only multiplies the controlled pressure value to higher flows and is almost the same for any type of the proportional valve. So measuring was pointed on the control circuit (pilot stage) of the valves.

For the test itself, proportional pressure regulating valves from company Festo were selected. They have a different construction of main working stage, but as mentioned before this issue has no effect on the overall electrical consumption of the valve.

One of the valves was a proportional valve type VPPE-3-1/8-6-010 with common on/off technology that is widely used for standard proportional valves (Fig. 10). This type of valve is an indirectly operated valve (piloted valve) which uses two 2/2-way valves to pressurise or depressurise the main membrane of the valve and thus controls the output pressure of the main working part.

Figure 10. Common proportional pressure regulating valve (Proportional pressure-regulator VPPE, 2025)

Second type was a proportional valve with piezoelectrical actuator VEAB-L-26-D9-Q4-V1-1R1 that directly controls the output of the valve (Fig. 11). This construction refers to a directly operated valves, but could be also used as a pilot stage instead of 2/2-way valves in common designs for larger valves with higher flow rates.

Figure 11. Piezoelectrical proportional pressure regulating valve (Proportional pressure-regulator VEAB, 2025)

Both valves have the same parameters regarding the control (Table 1). The difference is in construction and its nominal flow, but this fact has no influence, because tests were focused on the electrical energy consumption of the control circuit of the valves.

Table 1. Technical parameters

	VPPE type	VEAB type
Type of pilot	indirect	direct
Inlet pressure	6 – 8 bar	0 – 6,5 bar
Outlet pressure	0,15 – 6 bar	0,03 – 6 bar
Setpoint value	0 – 10 V	0 – 10 V
Accuracy AO	2,25% FS	2% FS
Nominal voltage	24 V DC	24 V DC
Nominal flow of main working stage	850 l/min	20 l/min

7 Measuring Setup

Measuring setup consisted of a PLC, two multimeters, proportional valve and a pressure sensor (Fig. 12).

PLC was used to control the analogue value. It was programmed to change the analogue setpoint for the proportional valve in time. Sequence was from 0V. After every 10 seconds the setpoint value was raised by 25% of full scale of the output (1,5 bar, 2,5 V) until it reached 100%. After that the setpoint value was set again to 0V. Time delay of 10 seconds was used for the valve to stabilise the output pressure to desired value.

Multimeters were used as measuring devices to check the analogue value from the PLC and also to measure the current that was used by the proportional valves during operation. Multimeter for current measurement was connected to PC to collect the measured data.

Pressure sensor was a visual feedback for the measurement to check the value of pressure at the outlet of the proportional valve.

Figure 12. Measuring setup

8 Results

The aim of the measurement was to collect information about the overall power consumption of the proportional valves during their operation.

Basic power consumption P refers to electrical energy E per unit of time t (eq. 1).

$$P = \frac{E}{t} \tag{1}$$

Electrical energy E is represented by current I floating thru a component connected to voltage V during time t (eq. 2).

$$E = U * I * t \tag{2}$$

As both proportional valves work with the same nominal voltage and the same testing procedure is used for all measurements, it is not necessary to calculate the power consumption. The ratio of power consumption of both valves can be represented by the current they used during operation.

Results of the measurement (Fig. 13) show the values of current consumption for each of the proportional valves. These values were calculated from 50 measurements as an average value.

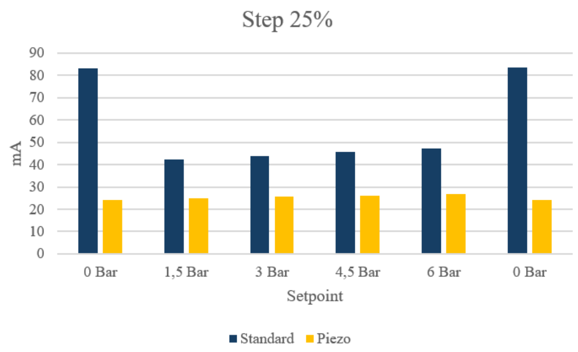

Figure 13. Results of measurements

Displayed values are a total consumption of the valves including electronics necessary to drive the valves and also the actuating stage (2/2-way valves or piezo valves).

9 Conclusion

Measured values of current consumption clearly show the potential in energy saving (Table 2). Energy saving potential is calculated as a percentage of overall energy consumption of a common solution with solenoid valves that can be saved using proportional technology instead.

Table 2. Energy saving potential

Setpoint (bar)	Analogue input (V)	Current cons. VPPE (mA)	Current cons. VEAB (mA)	Energy saving potential (%)
0	0	83,19	24,20	70,91
1,5	2,5	42,44	25,01	41,08
3	5	43,99	25,60	41,81
4,5	7,5	45,58	26,17	42,58
6	10	47,41	26,73	43,62
0	0	83,68	24,22	71,06

Energy saving potential changes in different parts of the working cycle. Maximum savings can be seen in standby state without regulation. In this state the savings go up to 70% which is given by the working principles of both valves. Standard on/off proportional valve uses energy to power the electronics and the coils to maintain the pressure of 0 bar. On the other hand, piezo proportional valve uses the energy only to power the electronics.

By setting the pressure to a certain value the consumption of standard on/off valve drops, because it deenergises one of the coils. Consumption of piezo valve rises by a small value but is still lower than the consumption of standard on/of valve creating an energy saving potential higher than 40%.

Use of proportional technology in pneumatic control valves can clearly reduce the power consumption of these components creating a huge space to save the energy. In our test, we saved between 40 and 70% of energy depending on the duty cycle. When used in larger quantities on automation equipment, this technology can significantly reduce the energy consumption of the output stages and thus also reduce the cost of production. Valves using piezo technology also have a wider variability in their application, enabling more flexible production processes and allowing us to move closer to the essence of Industry 4.0 or even wider. The cost of valves with piezo technology is higher than standard valves with coils, but their lower consumption and variability allows more sustainable and economical plant operation.

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