Vibration Operated Valve and Flow Metering Device for Abrasive Viscous Fluids

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Abstract

In this paper a new ultrasonic operated valve is presented. The ultrasonic valve design was analyzed and the valve was prototyped and tested for flow control of abrasive viscous fluid. This innovative valve concept is based on controlling the friction of material by employing several friction elements along the flow direction. Abrasive particles in the viscous fluid are stopped by the force of friction when coming into contact with the friction elements. Friction is neutralized by use of vibration to break away the abrasive particles from the friction element surfaces. In order to perform proportional flow control pulse width modulation was used to control the duty cycle of the ultrasonic power transferred to the valve. A study was performed to find the best vibration characteristics.

1 Introduction

Controlling the flow of abrasive viscous fluids has been a major problem, especially when the fluid contains relatively large particles of different sizes. Common problems include clogging, jamming of movable components of conventional valves, and cleaning of the valve after use. The challenge of this study, therefore, was to design a solid state vibration-operated valve that would provide steady, on-

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demand flow for abrasive viscous fluids at the desired rates, based on the following given information:

1. Required flow rate
2. Material friction characteristics
3. Desired pumping pressure
4. Pipe diameter, which affects the design of the starting section of the valve
5. Material density

1.1 Previous Attempts at Controlling Cementitious Fluid Flow

In the Contour Crafting automated construction project [Khoshnevis 2004], where control of concrete flow is a strict requirement, several attempts have been made to use available solutions or devise new solutions for flow control. First, a relatively small, progressing cavity pump was selected, which is shown in Figure 1. When this pump is used the flow pulsates as a result of the sequential output of discrete volumes trapped in the helical cavities of the rubber stator. Furthermore, the pump easily stalls if the proportion of sand exceeds a certain limit. Also the assembly is very heavy (nearly 70 kg) and hence is not suitable to be attached to the nozzle assembly which is supposed to be moved swiftly in the 3D space.

Figure 1. A progressing cavity pump driven by a large DC motor

A new dosing device was then invented by the authors. This device was significantly smaller and lighter than the progressing cavity pump system. This dosing device, shown in Figure 2, performed its function very satisfactorily but the rubber components used wore out rapidly.

Figure 1. A new dosing pump coupled to its driving DC motor

Use of proportional valves with feedback control was then considered. Subsequently, several valves were designed, fabricated and tested. For example, a pinch valve concept (Figure 3) using a latex tube, was devised. The tube was mechanically pinched by a blade that could reciprocate by

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means of a DC motor connected to a worm gear. The valve operated somewhat satisfactorily but had the occasional problem of segregation and clogging.

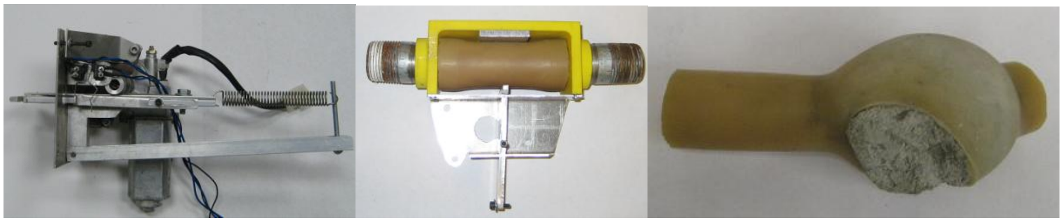


Figure 2.   Structure of a Pinch Valve and rupture of the latex tube due to valve failure and subsequent pressure accumulation

After testing the pinch valve, a new cut-off valve was designed and built. In this valve, pinching was avoided and instead a blade was implemented in the valve to obstruct the concrete flow. A schematic of this valve is shown in Figure 4.

Figure 4.   Mechanical Parts of the Cut-Off Valve

This valve had the problems of cleaning and blockage and it performed only as an open- close valve, that is, the valve was not able to regulate the flow and sometime it could not be fully closed due to obstacle of sand particles.

2   Mobility of Fresh Concrete

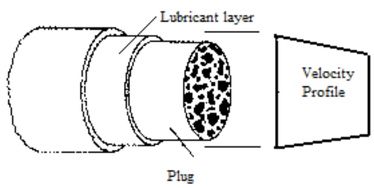
Concrete is a mix composed of a fluid phase and a solid phase. The fluid phase is the cement slurry and sand is the solid phase.

In mixed concrete particle assembly is composed of non-cohesive particles (aggregate grains) and cohesive particles (cement grains) surrounded by mixing water membranes. In the static state both particle groups are only subjected to the frictional resistance, but in the moving state only the former simultaneously bears the viscous resistance together with the frictional resistance.

2.1   The Flow of Concrete Along a Pipeline

The flow of concrete along a pipeline may be visualized as variously sized aggregate and cement particles suspended in water. Chiara F. Ferraris (2003) showed that freshly mixed cement paste exhibits non-Newtonian fluid properties, in that it has a yield point and a plastic viscosity which varies both with time under shear and also shearing rate. The addition of aggregate to cement paste further removes concrete flow properties from the Newtonian concept. When starting with new pipes it must be remembered that the internal surface of these pipes will be relatively rough compared with pipes that have been used for some time.

Loadwick (1970) discussed mobility of fresh concrete in terms of its viscosity, cohesion, and internal resistance to shear. Roger D. Brown (1977) created a model to relate the state of concrete in the pipeline to the mixed components. He established a pumping system to pump the concrete along a pipe and measured the mobility and pumpability of fresh concrete. He observed that a concrete mixture with excessive coarse aggregate results in a loss of cohesion and mobility. Base on his study, aggregate particle shape and size distribution are important factors influencing the rheology of the mix. Practical experiments with concrete exiting a pipeline show that it flows in the form of a toothpaste-like "plug" separated from the pipe wall by a thin lubricating layer (Figure 5).



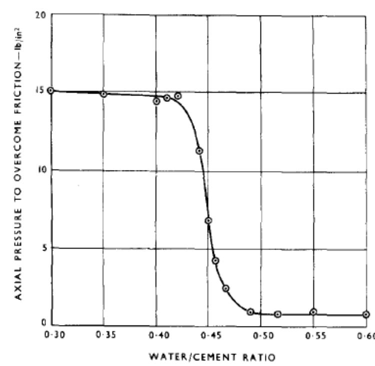


Figure 5. Concrete velocity profile along pipe *Figure 6. Pressure to overcome friction*

Source: Ede, A. N., "The Resistance of Concrete Pumped through Pipelines,"

Practice has shown that the pumpability of concrete depends on the proportions and characteristics (coarseness or fineness) of the mixture. This means that the cement content is of major importance and, in fact, concrete that lacks cement is not consistently pumpable (Figure 6).

At low stresses, the material behaves as a solid of extremely high viscosity. As stresses increase, concrete behavior gradually changes to that of a liquid.

2.2 Fundamental Principle of Vibration Valves

The novel vibration valve operation principle is based on the friction between abrasive particles within the fluid material and the inner walls of the flow conduit. The valve, therefore, works only for viscous materials that contain abrasive particles. Under the pressure applied to cause flow of the viscous fluid, abrasive particles accumulate along the flow path due to their inter particle friction with the conduit inner surfaces and dewatering. Moving these particles needs vibration to allow the passage of material. Vibration breaks the mechanical locking between particles and the walls of the conduit, and it also breaks apart the interlock between particles.

Figure 7 shows the friction concept between particles and the conduit walls. In this figure the friction caused by interlocking of abrasive particles and conduit surface is magnified by the "bridging" phenomenon. The pressure of incoming material against the middle particles of the arc formation causes the particles near the conduit surface to be pushed against the surface, hence increasing friction. Vibration of the conduit walls breaks away these mechanical locking, hence allowing the flow.

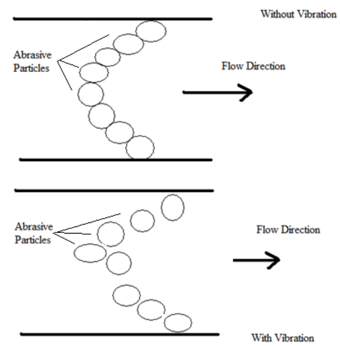


Figure 7.   Friction force between abrasive particles

3   Power Ultrasonic

The field of power ultrasonic, which represents an important field of industrial electronics, has experienced very swift and dynamic development in the past two decades. As a result, some systematic design and construction methodologies for new ultrasonic devices have been developed. Applications in the field of power ultrasound have extended into different branches and processes of many industries, including mechanical, electrical, and chemical.

The designed valve was connected to an ultrasonic converter via an interface. The best operating frequency of the ultrasonic converter is normally when the maximum traveling-wave amplitude is reached and when a relatively stable oscillation is established. The best operating ultrasonic systems are those that produce very strong mechanical oscillations or high and stable vibrating mechanical amplitudes, with moderate electric output power from the ultrasonic power supply. The second criterion is that thermal power dissipation of the total mechanical system, in continuous operation with no additional system loading, be minimal.

3.1   The Main Components in Ultrasonic Acoustic Vibration Generation

The main components in ultrasonic acoustic vibration generation are the following:

A) Ultrasonic generator, being an electronic ultrasonic signal generator. The converter, which is an amplification device for generating high power oscillating electric current from an electrical signal, is driven by an electronic signal generator.

B) High power ultrasonic converter, which converts electrical energy into high frequency mechanical vibration.

C) Booster, being a metal bar of, for example, aluminum or titanium, that as a mechanical wave guide connects the ultrasonic transducer with an acoustic load, oscillating body, or resonator; this can also boost the amplitude of input signal.

D) Acoustic load, which is the mechanical resonating body.

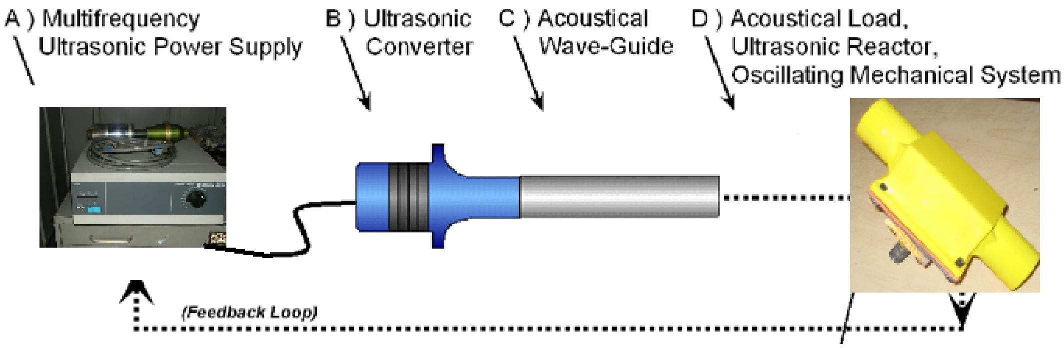


Figure 8. Schematic of generator, converter and load

The acoustic load, which in our case is the designed valve, was driven by incoming frequency and amplitude modulated pulse-train, causing it to begin oscillating in one or more of its natural vibration modes or harmonics.

4 Experimental Research

Because of the many variables that could potentially influence the consolidation of concrete, accurate and controlled measurements were made to prevent crediting the wrong variable for some measured response. In order to do so, experimental research was set up and many experiments were carried out. A Design of Experiment (DOE) was performed to study the impact of blade distances on both static friction tests and dynamic flow tests.

In order to begin the experiments, a new valve model was constructed. The schematic of this valve is shown in Figure 9.

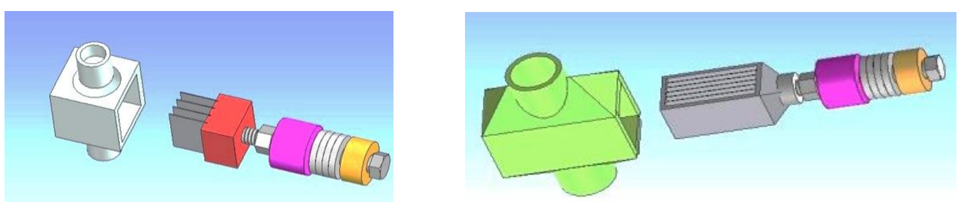


Figure 9. CAD models of the designed valve

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The horn in our system is the valve tip. The valve tip was designed by machining several blades along the path of concrete (Figure 4.2).

A method was devised for measuring the friction coefficient of the given viscous materials with the given planar valve blade surfaces. To achieve this purpose different valves with varying blade sizes were constructed as shown in Figure 10.

Figure 10. Valve-head varieties

In this research both clay and fresh concrete were used as sample materials. Concrete mass-per-volume for various mixes varied and was calculated from a measured sample. The fine aggregate used in this experiment consisted of different varieties including sand and silica. There was also coarse aggregate in the concrete mix, consisting of river gravel or crushed stone. The sand grain size was up to 5 mm.

Friction is influenced by material viscosity. In order to measure the viscosity the concrete was poured inside a cylindrical chamber rotating at constant speed. By measuring the variation of the torque exerted on the shaft driving the chamber over time the viscosity of the concrete was derived. Although the measurement was not entirely accurate, it was accurate enough to allow estimation of the range of material viscosity for the experiment. This identifies the friction coefficient used in our design procedure.

Before designing the experiments, the operational range for each factor needed to be determined. For example, pumping pressure needed to be adjusted, concrete could be made more viscous, and the sand size and proportion of sand in the mix could be adjusted. Determination of the maximum and minimum values for each factor was based on previous experience and a set of preliminary planned experiments. The preliminary experiments were based on one-factor-at-a-time variation.

5 Conducting Experiments

5.1 Static Friction Flow Stop Test

Here, several valves, with the same number and size of blades specified in the previous stage, were constructed. The valves differed with respect to inter-blade distances. Then for each valve a set of experiments was conducted with different materials and different pumping pressures. The data were input into a regression model and an equation was derived to relate flow to friction surface size, concrete pressure, and material characteristics (including viscosity and density). By putting the flow equal to zero, pressure to maximum, and having a standard material, the required surface to stop the flow in that condition was specified by computation.

5.2 Measuring Flow with Vibration

Vibratory friction reduction for viscous materials is achieved by setting the particles into motion, thus eliminating the internal friction. In order to accomplish this, the vibration test was conducted for each valve in the previously constructed set, with the vibration power set at a certain value. Then for each valve configuration different pressure values and different materials were used. The desired flow rate was determined by the required pressure, provided that the total valve friction in the ON state was known. To estimate the ON state friction an initial estimate of the pressure (i.e., the pressure of the material at the inlet of the valve) was measured and used in the design process. The results were put into a regression model and an equation was derived for the valve when in operation. Then by applying the maximum pressure and the calculated friction surface from the above we could find the flow rate when the valve was in the ON state. If the flow rate was in the desired range we followed the FEM analysis or the procedure of valve shape adjustment was started over again. If we wanted a greater flow rate, then we needed greater pressure. In that case the surface size required to stop the flow was greater than the previous amount. This pressure, which was identified experimentally in the design of experiments, was implemented after the design and construction of the valve.

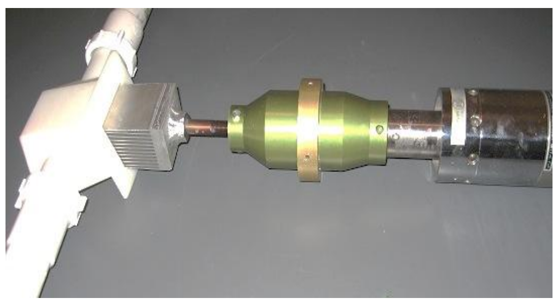


Figure 11. Vibration valve including transducer, booster and housing

5.3 Optimal Valve Shape

The challenge was to determine the number, size, and distance between the blades to be placed along the material flow path. The optimal valve shape was then selected through a process that began with an arbitrary starting design configuration that provided the requisite total blade surface area. A heuristic search procedure was then employed to converge toward the optimal (smallest with desirable form factor) design. Figure 5.2 shows some possible shapes of candidate valve designs.

The optimum valve shape is selected in such a way that maximum vibration energy is transmitted to each surface and it guarantees that each surface receive enough vibration to dispose material which is attached to its surface. If the attached material cannot be moved after a certain elapsed time the material would cure inside the valve section and hence would render that portion of the valve useless.

Usually longer dimension along the transducer axis or movement direction give better results for which dissipation of energy is minimized. An example of a desirable shape is the valve (b) shown in Figure 12. Also the valve should be designed in such a way that prolonged vibration does not induce excessive fatigue in certain parts.

The distance between blades was decided to be greater than the largest particle size. Subsequently the blades were designed in such a way that the total surface would equal the result from the above section.

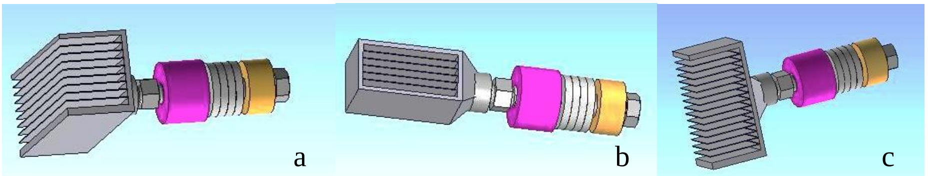


Figure 12. Possible shapes of candidate valve designs

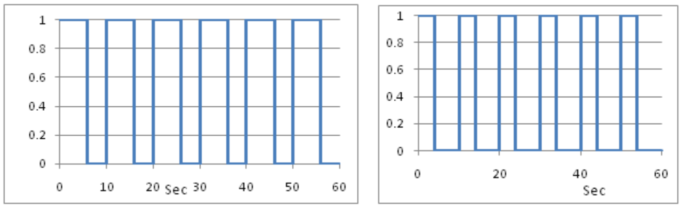
The objective function in the optimization process was the total active displacement (i.e., movement caused by vibration) of blade surfaces in the direction of flow. Other forms of vibration were considered as dissipative vibrations that result in power loss.

6 Controlling Flow with Duty Cycle

To achieve flow control a PWM (pulse width modulation) approach was used. The duty cycle of the pulse (i.e., the duration of vibration ON divided by duration of the OFF state) influences the overall flow rate through the valve. The preference here was to maximize the PWM frequency such that flow pulsation was minimized. Given that the fluid has mass, which is subject to inertia, there was a limit on the deceleration time of concrete mass due to the exerted friction force. At this stage two experimental activities were performed for each vibration power to identify: a) the duty cycle curve to achieve flow rates from zero to the specified (desired) maximum flow, and b) the curve relating the PWM maximum frequency to flow rate ranges.

The optimum duty cycle for each flow rate was the one that had the highest frequency (to minimize flow pulsation). Material mass inertia would prevent stoppage if the duration of OFF cycles were too short. In other words, if OFF cycles were long enough they would allow the material to reach the complete stop before the next start.

Flow control with duty cycle primarily depends on the generator response, and since in the case of the generator used in our experiments it takes about two seconds for the generator to start after each stop, any duty cycle with an ON less than two seconds did not measurably affect the flow rate.



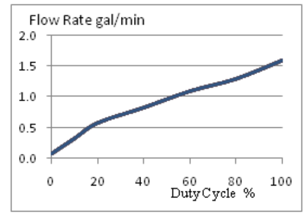


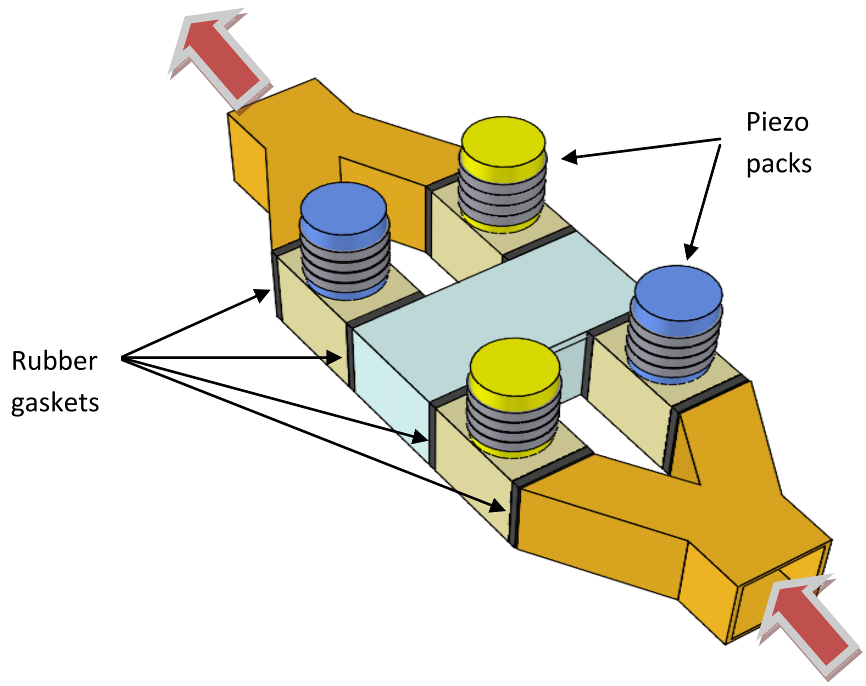
Figure 13. 60% duty cycle 40% duty cycle Figure 14. Flow versus duty cycle

It was revealed that the material flow has linear relationship with duty cycle. The slope of the chart in lower duty cycle is different from the higher duty cycle and the reason is mostly related to generator response in lower duty cycles (Figure 14). By using more responsive generator accuracy is increased and the curve can become more linear. A programmable logic controller (PLC) was used at this stage to control the frequency and duty cycle of the pulses to the generator.

7 Open-Loop Flow Metering

It is possible to integrate four piezo-actuated valves with a free moving piston which can reciprocate in a chamber to create an open-loop flow metering apparatus. The configuration is shown in Figures 15 and 16. Note that that the four piezo valves marked by A, B, C and D which are all connected to a block shaped chamber (light blue) turn on and off in a pair-wise fashion. Pressurized viscous and abrasive fluid is simultaneously introduced to valves A and B at the inlet. When valves A and D are in their open state (i.e., being vibrated by their corresponding piezo packs shown in Figure 6) while valves B and C are closed, the material flows through valve A, enters the chamber and then pushes the square piston (shown in orange) to its extreme position to the right where it stops when it reaches the end of its stroke. While being pushed to the left the piston pushes the fluid on its left side out through the open valve D. The cycle is then switched such that valves A and D are closed and valves B and C are opened. In this state the square piston is forced to the left side in which case it pushes the fluid at its left side out through the open valve C. If pressure is high enough the movement of the piston would be sudden. A pre-selected delay between each cycle ensures that the piston reaches the end of its stroke after each half cycle. In this manner, each half cycle transfers a volume of material, which is equivalent to the volume of the chamber along the stroke range of the piston. Consequently, by controlling the frequency of the cycle one would be able to accurately dose the fluid with a resolution, which is equal to the volume of the chamber.

In another embodiment a sensor (such as a Hall-effect sensor) may be placed outside the chamber near each end of the stroke range of the piston. If a magnet is placed inside the piston then arrival of the piston to each stroke end may be detected. This configuration would assure that the cycle frequency is made long enough for the piston to make its complete reciprocation, hence ensuring reliable dosing control.



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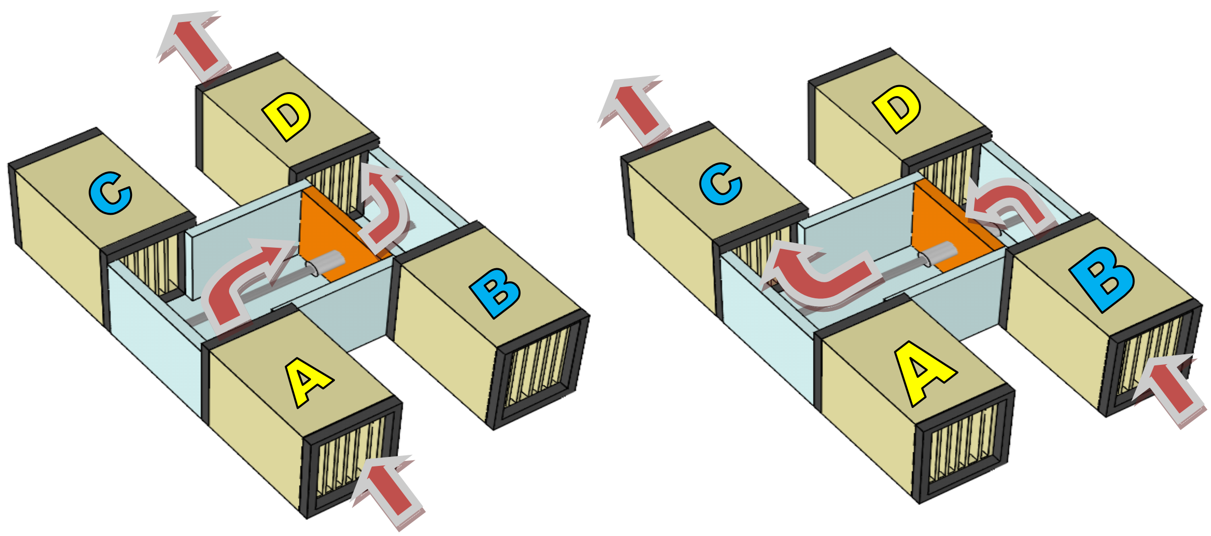
Note the rubber gaskets used in the design of the device isolate the vibration and prevent its transfer (and hence loss of energy) to the



non-valve sections of the device.

8 Conclusion

Vibration operated valves have certain unmatched advantages in comparison with other valve soultions for cementitious material flow control. Most notably, such valves do not have mechanical moving parts that could jam and they lack rubber components that are prone to rapid wear. Other valves used for flow control of fluids with abrasive particles are bound to use rubber and hence their

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Figure 16. Operation of a piezo activated fluid metering device

useful life is very limited. Another drawback of conventional valves is the inability to perform proportional flow control due to the aggregate bridging phenomenon which could completely shut down the flow (due to clogging) in partially open valve states. Such problems make it impossible to use the conventional valves in continuous flow control mechanisms such as PID based configurations. Vibration based valves and flow metering devices seem to be ideal candidates for such applications.

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