

Design Practice - 2
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Lecture - 20
Designing of the Micro-Valve

Hello and welcome to this Design Practice 2 module 20. So we were talking in the last lecture about the pneumatic valve design shown and represented in this diagram right here.

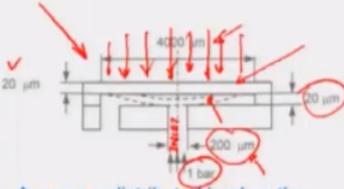
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Micro-valves

- The power consumption of the valve is the total input power of the valve in its active power consuming state.

The power consumption may be very small (for electrochemical valves) to very large (for thermopneumatic valves).

Designing a Pneumatic valve



A pneumatic micro-valve has a circular silicon membrane as the valve seat. The membrane is 20 microns thick and has a diameter of 4mm. The valve is normally open with a gap of 20 microns between the membrane and the valve inlet. Determine the pressure required for closing the valve at an inlet pressure of $p_{in}=1$ bar. The opening diameter is 200 microns.

Assume a distributed load on the valve membrane, a Poisson's ratio of 0.25 and a bulk Young's modulus of silicon of 170GPa.

Some of the parameters that are there are that the micro-valve has a circular silicon membrane and which acts as a valve seat. The membrane is about 20 microns thick which is given right here and has a diameter of about 4mm, 400 microns. And the valve is normally open with a gap of 20 microns. So this distance right here is 20 microns when it is normally open between the membrane and the valve inlet. This is the inlet, so I will just write the inlet channel here.

This is the inlet. The idea is that this membrane will bend down as you are seeing in the dotted region here and it will close the inlet so that the valve can come to the closure position and you have to determine the pressure required for closing the valve at an inlet pressure of 1 bar. So you are wanting to determine what is the pressure requirement on the other side of this membrane so that you know a total pressure of 1 bar inflow could be controlled, could be blocked given that

the opening diameter is about 200 microns where this whole pressure is being exerted and we have to assume a distributed load on the valve membrane.

So we cannot assume a point load here. It is as if cylinder is giving air pressure okay something like that and so it is well distributed load on the whole membrane, the blocking membrane or what you call the valve seat. And you have a Poisson's ratio of about 0.25 and a bulk modulus of 170 GPa for silicon material through which this valve has been constructed. So let us do some preliminary calculations.

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For a small deflection, the spring constant of the uniformly loaded valve membrane is estimated as:

$$K = \frac{16\pi E t^3}{3r^2(1-\nu^2)}$$

E = Bulk modulus
 t = Membrane thickness
 r = Membrane radius
 ν = Poisson's ratio

$$K = \frac{16 \times 3.14 \times 170 \times 10^9 \times (20 \times 10^{-6})^3}{3 \times (200 \times 10^{-6})^2 \times (1 - 0.25^2)} = 6.08 \times 10^3 \text{ N/m}$$

Let's assume that the membrane is closed at P_{air} , the force balance on the membrane is:

$$P_{air} A_{eq} = P_{in} A_{open} + F_{spring}$$

At equilibrium at valve closure 2
 at valve opening 1 as a deflection spring

So for a small deflection, the spring constant of the uniformly loaded valve membrane is estimated as K equals to 16 pi E cube of t divided by 3 r square 1 minus mu square. I am just going to refer the various terms here. E is the bulk modulus, t is the membrane thickness and this is from standard strength of material knowledge that the computation for K or the solution for K is being borrowed. R is the total radius of the membrane.

So I call this membrane radius and mu is the Poisson's ratio or the material in this case it is silicon. So the Poisson's ration has been given out to be about 0.25 in this particular case. And we want to calculate what is the value of K for this particular problem. So therefore, K comes out to be equal to 16 times 3.14 value of pi times of the total bulk modulus which is about 170 gigapascal. So I write it 170 10 to the power of 9 Pascal times of cube of t.

You know the thickness t is given out to be 20 microns. So we have 20×10^{-6} meters and cube of t divided by $3r^2$, r in this particular case is about 2 mm. If you remember the total diameter here is about 4 mm as can be seen in this of the whole valve membrane. And so we are going to go half way when it is radius 2000 microns or 2 mm. So we have square of r which is 2×10^{-3} square times of $1 - \nu$ square as the Poisson's ratio and this is found as 6.08×10^3 N/m.

So that is the equivalent spring constant that is found in this particular case for the silicon membrane which is going to be acting as a valve seat. So let us assume that the micro-valve is closed at an actuation pressure P_{act} and this pressure per se falls on the top of this membrane. So you know that the closure can only happen if there is some kind of a uniform loading and in terms of force per unit area or pressure on the free end of the membrane, the micro-valve membrane.

So if you assume this area of the interface to be A_m let us say, the area of the membrane, so we have P_{act} on one side and on another side the inlet pressure. So if we further assume the area of this opening right here to be A_{open} okay, we can have a force diagram of this particular system so the force balance on the membrane is $P_{act} \times A_m$ equals the inlet pressure times of area of the open channel A_{open} plus the spring force that the membrane has to exert which is towards the opening side.

Because obviously your bend holding the pressure inside this particular pipe you know or in this particular inlet wing and for that whatever force is needed to bend the spring is going to give a reverse force as if the spring were open and it would try to close. So it will give exactly Kx force where K being the spring constant. So K has already been calculated in this particular case. So let us calculate this force balance equation for two different conditions.

One when the valve is in an equilibrium state and let us say we are talking about the equilibrium at valve closure. And we can also find out the total amount of you know how this equation behaves at valve opening okay as the actuation begins. What is interesting in this case would be

that both these values are quite dissimilar and one has to design for all this when you are talking about such a actuated design okay which is going to do valve, valving okay at this particular scale.

So case 1 is corresponding to when the actuation begins and case two is corresponding to when it is in equilibrium. So let us understand properly what happens to case 1 that is when actuation has begin to happen, actuation begins.

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Case 1: When actuation begins $A_m = (\pi r_m^2)$

$$P_{eq}(A_m) = P_{in}(A_m) + F_{spring}$$

$$P_{eq} = P_{in} + \frac{F_{spring}}{A_m}$$

$$= 10^5 + \frac{1.08 \times 10^3 \times 20 \times 10^{-6}}{2.14 \times (2 \times 10^{-3})^2} = 1.09,177 \text{ Pa}$$

Case 2: When the valve is in closed position or equilibrium
 P_{eq} needed would be much lower

So you have a case where you have the P act on one side with the membrane radius and the area therein, the area A_m in this particular case as you may recall is given by πr_m^2 where r_m is the 2 mm radius of the circular valve orientation which has been defined earlier. So this becomes equal to that on the inlet site again πr_m^2 ; please understand when we are talking about beginning of actuation, the whole inlet pressure is available on the lower side of the membrane because the membrane has not reflected or moved.

And so the membrane is being upheld by the inlet pressure which gets into this particular channel and before moving out would create through the Pascal's law an equal pressure in all directions. So here the P_i or P_{in} times of πr_m^2 plus the spring force is what makes up the force balance equation. We can divide by πr_m^2 . So we have P_{inlet} plus the total spring force Kx in this particular case divided by πr_m^2 , inlet pressure being equal to 1 bar, the spring

force being equal to the K value times the total amount of deflection that it has to withstand which is 20 microns.

For opening to closing you have to cover this particular distance of 20 microns okay divided by 3.14 times 2 10 to the power of minus 3 square. So that comes out to be equal to about 109,677 Pa. So this is how the beginning pressure is when the valve actuation has started. However, in this particular case you may observe that when the valve actually closes, so much of pressure may not be really needed okay. This is going to change when it is at equilibrium.

So the actuation force or the actuation pressure is going to be the highest pressure in this particular case. So this gives you an idea of how you are designing a valve actuator okay. in the same manner I am going to do a few things you know in the next few minutes with you which talks about such actuation principles and designs. So here in this case, in case 2, let us say when at equilibrium when the valve is in closed position at equilibrium the P actuation needed would be much lesser.

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$$F_{spring} = K \times 20 \times 10^{-6}$$

$$\therefore P_{act} \times \pi \times (2 \times 10^{-3})^2 = \underbrace{10^5 \times \pi \times (1 \times 10^{-3})^2}_{\text{Valve inlet area}} + 6.10 \times 10^3 (20 \times 10^{-6})$$

$$P_{act} = \frac{7.25 \times 10^3}{\pi \times (2 \times 10^{-3})^2} = 72.5 \text{ kPa} \quad (101,325 \text{ Pa})$$

Actuation demands a lot more energy (pressure) than maintaining this closed state. (98 kPa)

Obviously, the fundamental that is kept intact here is that the spring force of forces K into 20 minus 6 and the actuation force times of the total membrane area becomes equal to the total amount of inlet pressure times the inlet area which is only 0.1 in this particular case okay. You

know that the opening dia here has been given to be about 200 microns. So that is about 0.1 mm radius. So let us put this value back here.

So we have 0.1 times of 10 to the power of -3 square as the force on the inlet site. You have to consider the valve in closed position where the only exposed part of the valve lower membrane okay is 0.1 mm radius circle okay, valve inlet force. So this plus the spring force which is in this case 6.08 10 to the power of 3 times of the total movement that has happened which is 20 microns and in this case if I calculate it what is the actuation pressure, it comes out to be equal to 9.85 10 to the power of 3.

That is about 9850 Pa. So it is very clear that actuation demands a lot of more energy in this particular case than equilibrium and closure, demands a lot more energy in this case. Energy is of course given externally by a mechanism which would exert pressure on the membrane which will close the flow. So it demands a lot more energy than maintaining the closed state. Here the total amount of pressure needed is about close to 109677 Pa whereas in the closed state you only need about 9850 Pa.

This is true for all actuator systems that when we are talking about start of actuation which leads to a certain end effect. It is almost always that more energy has to be pumped in the system than the end of the actuation. So we will design the corresponding thermopneumatic version in this particular case. I am going to twist the problem a little bit.

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Designing a Thermopneumatic valve

If the valve described in the earlier example is designed with a thermopneumatic actuator on the top of a membrane. The actuator chamber is a cylinder with a height of 500 microns. If the chamber is filled with air and hermetically sealed, determine the temperature required for closing the valve at an inlet pressure of 1 bar. The initial pressure and temperature in the chamber are 1 bar and 27 deg. C

Assuming that the volume of the chamber is constant, the relation between temperature and pressure is :

$$T_1/T_2 = P_1/P_2$$

$$T_2 = T_1 (P_2/P_1) = 300 (109677/100000) = 329 \text{ K} = 56 \text{ deg. C.}$$

And here what we simply say is that the valve described in the earlier example is designed with a actuator which is of thermopneumatic type on the top of the membrane thereby meaning that there is a cylinder on the top which has a fixed volume containment or a confinement and heaters which would heat the gas and so the gas inside the confinement would actually follow the Charles law of you know pressure being proportional to the temperature.

So with the temperature rise obviously is going to give more and more pressure on to the membrane thus deflecting the membrane and blocking the valve. So in that event what is going to be the temperature required for closing the valve okay. We will assume the same inlet pressure of 1 bar as earlier and we can assume the initial pressure and temperature of the chamber to be 1 bar and 27 degree Celsius respectively.

Obviously, we assume that the chamber is filled with air and hermetically sealed so that there are no heat outlets from the system. So assuming that in this particular case, the chamber is constant. The relation between temperature and pressure if it is hermetically sealed and if there is no heat inlet outlet to the chamber except the heater which delivers the heat inside the chamber itself.

So you have T_1 by T_2 that is the temperature ratio between the initial temperature T_1 and the final temperature T_2 being proportional to the pressure ratio that is P_1 by P_2 and so therefore the temperature that is needed for a pressure rise which is equal to the force needed for actuation,

in this case you already found out the total amount of pressure that is needed for actuating or start of actuation of the valve is 109677.

This comes out to be equal to the pressure ratio between the actuation pressure and what it was earlier at. The pressure was earlier at 100000 1 bar inside the cylinder okay and the earlier temperature was 300 degrees. It has been mentioned here 27 degree or 300 degree Kelvin okay. So total amount of temperature that is needed for this process to execute the valve closure and then becomes about 56 degree Celsius or 329 Kelvin.

So that is how you design a thermopneumatic system. So there can be many such forms of you know systems which are used by various you know different valves. They particularly can operate on a lot of conditions for example there can be as I told you thermomechanical valves. There can be piezoelectric valves. There can be electrostatic valves. There can be electromagnetic valves so on so forth.

So we would now like to design another set of actuator that is an electrochemical actuator which would be playing the role of an electrochemical microvalve. Of particular importance here for me to tell you is that such valves are very commonly available within microflows and microfluidic systems because they are typically electrically driven and it is always better from a integration possibility into a chip scale, so microchip scale. So this is what we want to do here.

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Electrochemical Valves

(a) Outlet

(b) Capillary-force valve

Typical Electrochemical Valves (a) Gate Form (b) Capillary form

Electrochemical valves are actuated using gas bubbles generated by electrolysis of water:

$$2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$$

Determine the energy required for generating an electrolysis spherical bubble with an approximate diameter of 28 microns. Compare it to a thermal bubble of the same size. The specific density of hydrogen and oxygen at 1 bar and 25 deg. C are .08988 Kg/m³ and 1.429 kg/ m³, respectively. The surface tension of water is assumed to be constant at .072 N/m. Enthalpy of formation of water is 285.83KJ/ mol. The thermodynamic properties of liquid water at 1 bar are v (25 Deg. C) = 1.0029 X 10⁻³ m³/kg, u (25 deg. C) = 104.88 KJ/Kg and of vapor: v (100 Deg. C) = 1.673 m³/kg, u(100 deg. C) = 2506.5 kJ/Kg.

We have case 1, a certain layout of the electrochemical valve where there is a inlet of a flow coming from one end and an outlet going to this end and there is a possibility of this electrochemical bubbles which are being formulated by hydrolysis of water and there is a reaction element which is there where H₂O is converted into hydrogen and oxygen gas and obviously because there is a certain dissolution rate within the medium which may be quite different than the formation rate and formation rate maybe much ahead of the dissolution rate.

So whatever is not dissolved is stored inside the water as a pocket, so it becomes a bubble okay. So it is a 2 phase bubble where there is a gas phase which is being surrounded by the liquid water, part of which has been hydrolyzed into the gas and so such bubbles and the way that it grows or the rate at which they grow can be customized in a manner which would lead to eventually the movement of this gate.

So for example if these 2 bubbles right here are smaller or their growth rate is smaller in comparison to the bubbles which are at the backend here then obviously the gate will move forward and supposing is the other way around that the 2 bubbles at the so in the closed position of the valve, the 2 bubbles at the front end are being created at a much higher rate in comparison to the bubbles at the back, so it may lead to a reverse possibility that is the gate going back and allowing the flow to happen. So this is one version.

The other version could be in terms of a bubble which you are formulating in a channel. This bubble right here generated somewhere inside this micro channel may become so big that it starts blocking all the inlet from going through this small constriction which is there. So obviously the total amount of bubble pressure which has to be there should be enabled to take the inlet pressure and still retain its property of being a bubble.

So one of the advantages that microscale flows have is a lot of difference in the physics. It is more surface based physics where effects like surface tension etc. has a predominance over the volume effects like density, pressure, etc. So electrochemical valves in that range work very well. And so the whole idea is to design again an actuator or a valve which is based on electrochemistry as I showed you just above here in the 2 cases.

Some of the parameters have been given. So we would like to determine the energy required for generating an electrolysis driven spherical bubble with an approximate diameter of 28 microns and we would like to generate this bubble electrochemically and compare it to the amount of thermal bubble effort you know. So if supposing there is a equivalent bubble created by just heating and vaporizing.

So what is going to be the difference in terms of energy in both the cases, in the electrochemical as well as the thermal cases particularly if the bubble were of the same size okay. Some parameters have been given here for example specific density of hydrogen and oxygen had been given at 1 bar pressure and 25 degree Celsius, is a standard temperature conditions, standard temperature and pressure conditions, STP conditions and they are 0.08988 kg per meter cube and 1.429 kg per meter cube respectively.

Similarly, a component related to surface tension of the water has been given. So it is very important to see what are the pressure differences which should be sustained by the bubble okay. pressure differences between inside the bubble and outside the bubble. So we will try to design it on that basis. Surface tension of water is given at 0.072 N/m and we have some other parameter and then we have some other parameters including enthalpy of formation of water which is actually related to the way that this electrochemical reaction happens.

This is the enthalpy for this particular reaction and some thermodynamic properties of liquid water particularly at the same pressure level, at the same temperature level that is you know the total amount of specific volume or the internal energy that the bubble will have formulated thermally. And further these parameters that is specific volume as well as the internal energy are given at the boiling point as well as the room temperature point.

So there is obviously going to be a change in these properties as the temperature goes up. So given all these parameters, let us have you know a discussion probably in the next module as to how do we compare these 2 processes in terms of the energy requirement so that the actuation can happen electrochemically and we would get an understanding, a fair understanding of you know the very fact that an electrochemical you know actuation techniques the demand for energy maybe much more in comparison to the thermal technique.

So we will round off this module here but in the next module we will try to do design of this particular valve. As of now thank you very much. I will see you in the next module. Bye.