Cryogenic Engineering
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Lecture No. # 29
Cryocoolers
Ideal Stirling cycle

So, welcome to the 29th lecture on cryogenic engineering; in the last lecture, we were talking about Stirling Cryocoolers.

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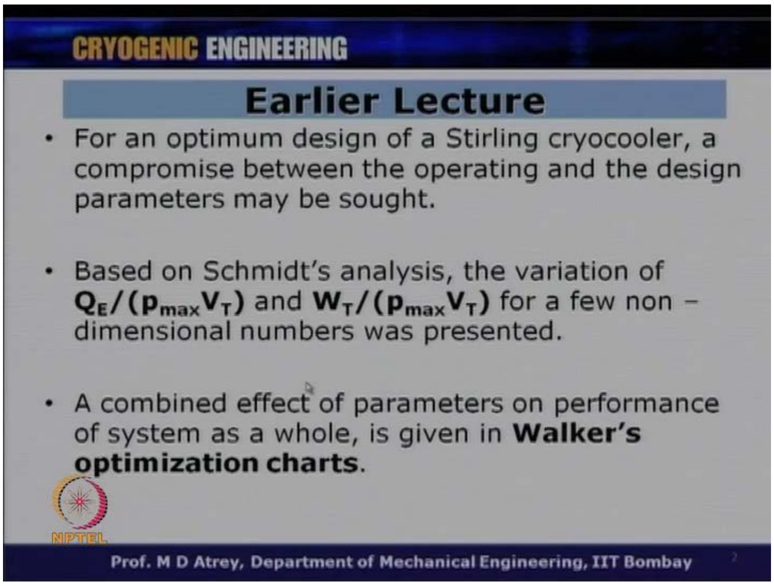

In fact, we touched upon various aspects of design on Stirling cryocooler and we found that for an optimum design of Stirling cryocooler, a compromise between the operating and the design parameters may be sought. So, you got to compromise between the dimensions and various operating parameters like pressure, frequency etcetera also we had study Schmidt's analysis. And we found that based on Schmidt's analysis, the variation of Q E divided by P max into V T, which would called as Q max and W T upon P max into which we called as W max, for a few non-dimensional numbers was presented. So, we understood how this parameter Q max and W max vary with respect to various parameters, a combined effect of parameters on performance of system as a whole, was given by Walker's optimization chart and we saw how these charts look and how do we use these charts for initial design of Stirling cryocooler.

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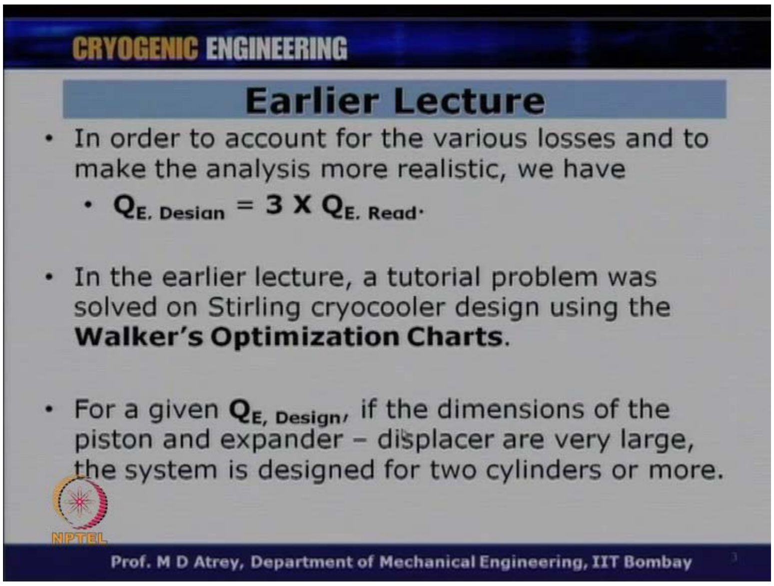

Also we understood that, in order to account for the various losses and to make the analysis more realistic, we took some Q E design value that is cooling effect required for designing aspect and that we took as 3 times Q E required. So, actually required Q E is suppose 1000 watts, we designed the cryocooler for around 3000 watt or 3 kilowatt. This was basically to take into consideration the account of various losses because we did not go in the details of calculation of each of the losses alright. So, this is a kind of a factor of safety which is used to design a Stirling cryocooler using Walker's design chart.

In the earlier lecture, a tutorial problem was solved on Stirling cryocooler design using the Walker's Optimization Chart. And when you say design, we basically intend to calculate the diameter of the piston, the stroke of the piston diameter of the displacer and the stroke of the displacer, which in turn decide various others diameters of which we did not go into details of those dimension calculations. For a given Q E Design, if the dimensions of the piston and expander-displacer are very large, the system is designed for two cylinders or more.

So, for a given cooling capacity, if we found that the diameters are coming very large then, we can conclude that this is not possible using one cylinder. But we may have to go for two cylinders or even if there in the diameter comes very large then, we have to go for four cylinder like that. And therefore, a four cylinder machine can; now, generate lot of cooling effect than a single cylinder machine basically, like any other automobile also if you want to compare this with.

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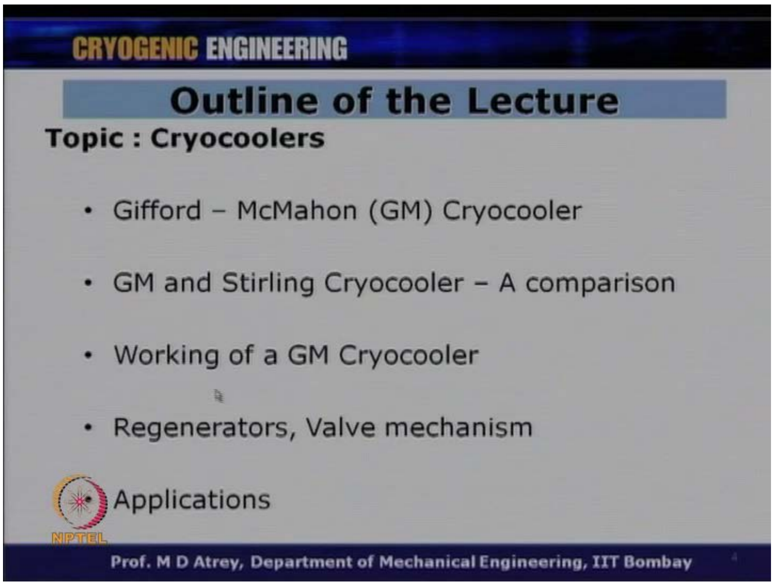

So, that is what we had talked about during the last lecture on Stirling Cryocooler and extending this topic further on Cryocoolers here in this particular lecture we will talk about Gifford-McMahon or (GM) Cryocooler. So, we will talk about, also we try to compare the GM Cryocooler with Stirling Cryocooler and this comparison is very important for you to understand. Then, we see how this GM Cryocooler works I have got some schematics so, that we as understand how GM cycle, or GM Cryocooler works. Then, the various important aspect related to regenerator especially, the regenerators at low temperature valve mechanism how do they function, I will explain that. And let us lastly we have some commercial applications of GM Cryocooler, just to explain a few of them.

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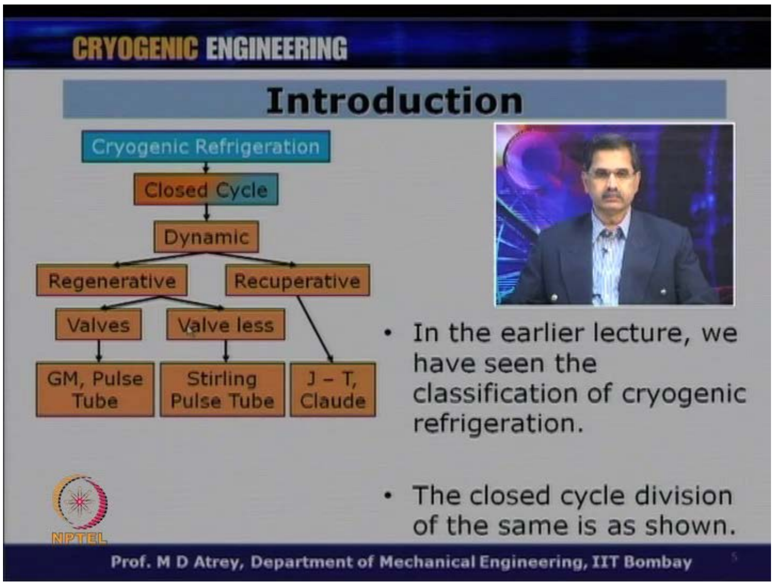

So, in the earlier lecture, we have seen the classification of cryogenic refrigeration and from here, we can find out where the GM cooler lies? So, GM cooler lies somewhere over here, we found that for a closed cycle version. We have got a dynamic, in dynamic we have got a regenerative and recuperative heat exchanger and under regenerative you have got a valve and no valve, valve and valve less system.

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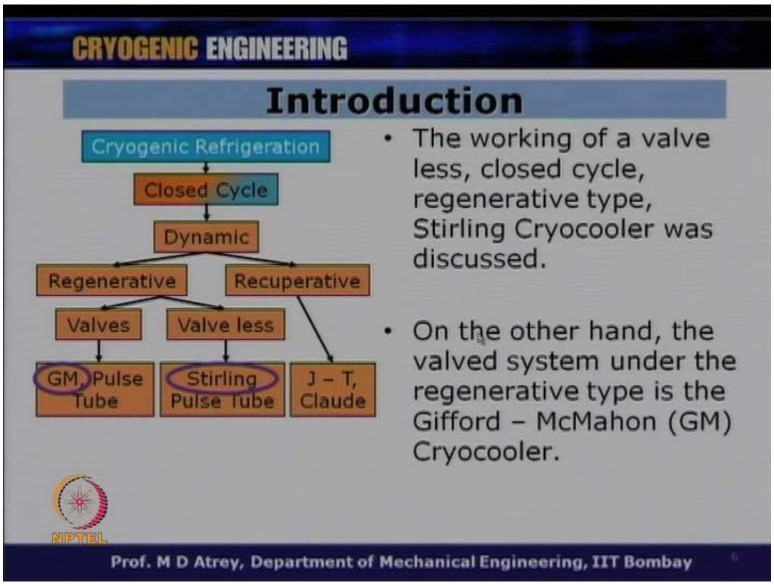

The Stirling cooler comes under the valve less category. The working of a valve less, closed cycle, regenerative type, Stirling Cryocooler that is what we had discussed that means, during the last lecture, we concentrated on this type. And in this lecture now, we are talking about this that means, a regenerative cryocooler with valves and that is of GM cooler. So, on the other hand the valved system under the regenerative type is the Gifford-McMahon Cryocooler on which we are going to talk in this lecture.

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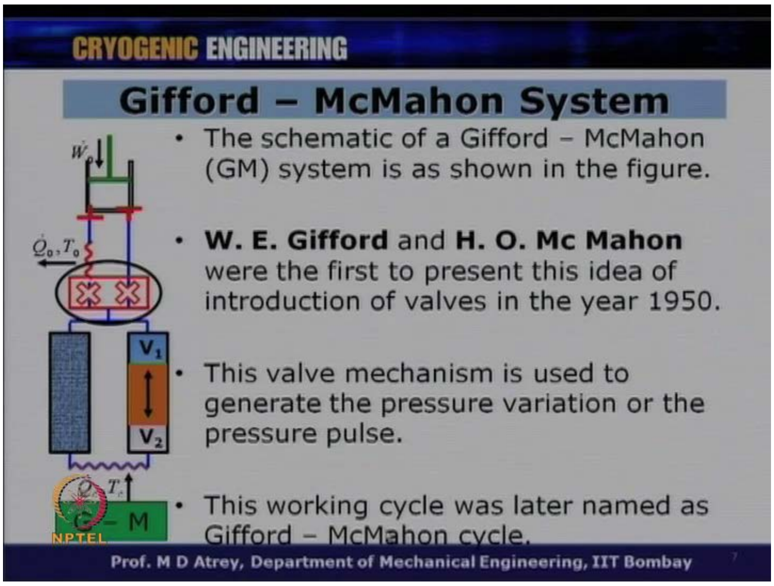

So, how does this look like, a schematic of a GM Cryocooler looks like this, we had talked about this earlier. So, we have got a piston here, which is oscillating the piston will generate high pressure and low pressure. That means, here with these valves which are inbuilt in the system or the no-return valve here. Here the high pressure and the low pressure side gets divided this was not so in a Stirling cycle. If you try to compare each and every place of GM cooler, it is very good to understand from this that the output from the compressor was only one and not two here. So, in this case, we have got two outputs one is the high pressure and one is the low pressure, after the gas gets compressed the high pressure here heat is removed at this point and then it has got a valve mechanism.

A Gifford-McMahon Cryocooler was basically invented by W E Gifford and H O Mc Mahon were the first to present the idea of introduction of valve in the year 1950, as old as 60 years around this valve mechanism. Now, this is the valve mechanism, which basically exist between the compressor and the expander. If I call this region as expander and this as compressor, the valve exist between these two. This valve mechanism is used to generate the pressure variation, or the pressure pulse. So, the high pressure valve gets opened for some time and therefore, the expander is subjected to high pressure, the gas comes in the expander. And after some time, the high pressure valve gets closed and the low pressure valve opens thereby having expansion of the gas over here and you get lowering of temperature, this is what we will see in the GM cycle. This working was later called as Gifford-McMahon cycle or shortly GM cycle.

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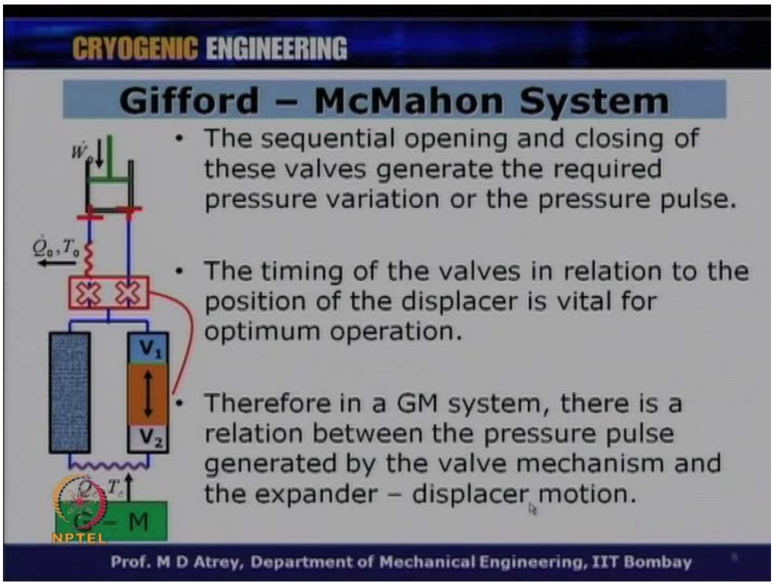

The sequential opening and closing of these valves generate the required pressure variation or the pressure pulse. Now, all depends on the opening and closing of this valve, in earlier case what we had was sinusoidal pressure variation for Stirling cycle. Now, here we can have any waveform for a pressure pulse and that can be incorporated, that can be produced by this rotary valve. The opening and closing of this valve will determine what kind of wave, do you want to go straight up, stay for some time come down to low pressure stay for some time. So, in short you can have basically a very closed loop kind of a trapezoidal wave in this case and everything depends on the design of the this rotary valve.

And therefore, this rotary valve plays a very important, normally in a GM cooler you will not have a sinusoidal variation of the pressure pulse, but you will possibly have a kind of a trapezoidal wave in this case. Also the timing of the valves, the opening and the closing of this valve is in relation with the position of the displacer and this is very vital for optimum operation. So, when this my high pressure valve opens, according to that the displacer motion should basically get influenced by; so, when this valve open there should where should this displacer be, when low pressure valve open where should this displacer be. And therefore, the movement of this displacer is going to be in accordance with the rotary wall motion and we will see that in a GM cycle when I explain to that after a couple of minutes.

So, here I have to worry about a rotary valve opening and according to this the displacer should move up and down, this is very important. Therefore, in a GM system, there is a relation between the pressure pulse generated by the valve mechanism and the expander or the displacer motion this is what I just talked about.

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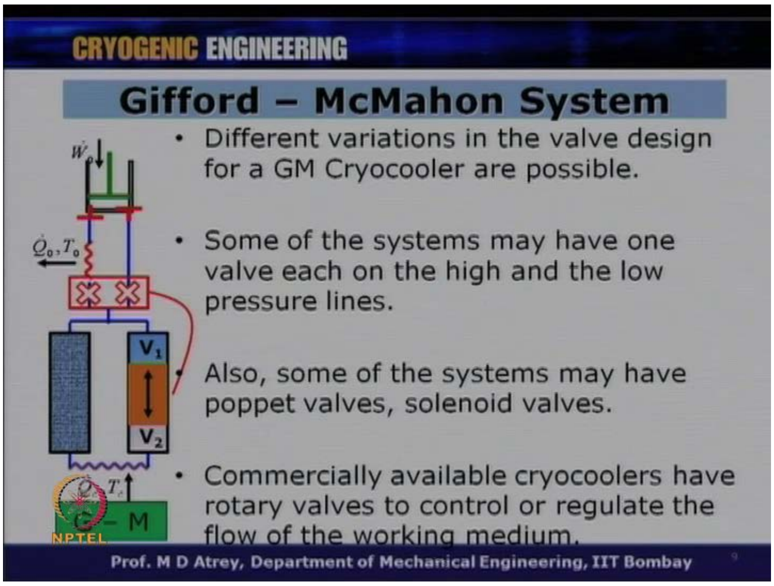

Different variations in the wall design of a GM coolers are possible, some of these system how do these valve work what kind of valve this is basically. So, we can have various version of this lot of manufacturers use different kinds of valves and most of the details cannot be made public. Some of the systems may have one valve each on the high and the low pressure sides so, you can have a valve on this side, you can have a valve on this side and this valve opens and close. Also some of the system may have poppet valves, like in I C engine you have got a poppet valve, spring-loaded valve and therefore, such valves also could be used. If one wants to it will have different you know losses, loss mechanisms and things like that, some of them can have even solenoid valves.

So, you can have a pneumatic control, you can have electrical control over there in the opening and closing backgrounds of these particular valves. Mostly, however, in commercially available cryocoolers they use something called as rotary valve that means, there is a motor which drives this valve. And this motor goes on rotating continuously and during the revolution of this motor at some point in time the high pressure valve opens and at some point in time it gets closed and the low pressure valve opens. So, normally a rotary valve is open is working there to control and regulate the flow of the working fluid alright. So, normally it will be a rotary valve and once I say rotary valve, it will have a motor to give a rotary motion.

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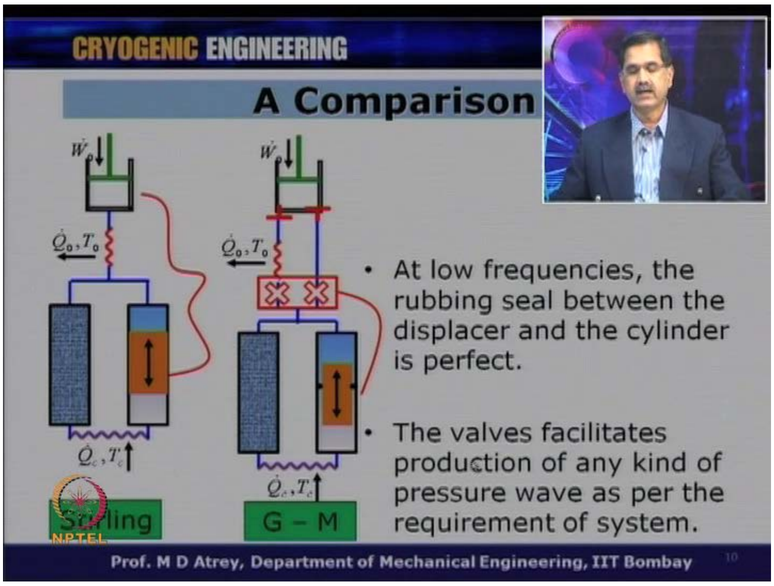

So, you can see here, if I want to compare a Stirling Cycle Cryocooler and a GM cycle cryocooler so, you can see both the units together, both the schematics over here, directly it reveals that there is no valve here, there is a valve here alright. I have shown this connection that means, the piston and displacer has a fixed phase difference, this is what we've talked about in this Stirling cycle cryocoolers. So, this displacer motion is having some relationship with the piston motion and the compressor, while that is not so in a GM cryocooler. The displacer motion is in relationship with the opening and closing of this rotary valve here that means, it is not bothered about what is happening on this side.

As long as I get a pressure pulse on this side after the rotary valve, we should be in relation with displacer motion, which is going up and down this is very critical alright.

So, this rotary valve normally works at very low frequency, as compared to that of Stirling cryocooler. Now, one again, one more aspect is because they are in going in a phase difference with each other, the frequency of this piston is going to the frequency of the displacer, while it is not so over here. The frequency of the rotary valve opening and closing is going to be the same, which is driving the frequency of the displacer motion, this is very important. This displacer has nothing to do with the frequency of the piston alright these are very aspect, if I want to compare Stirling cryocooler with a GM cryocooler.

So, here you can see, because this works at a low frequency you can see the sealing works very fine while a sealing, will be absent in kind of a Stirling cooler because it moves very fast, this sealing is kind of a rubbing sealing across the cylinder. And therefore, at low frequency this sealing could remain perfect, while at high frequency this sealing will never remain perfect, because it is a rubbing seal. And therefore, in Stirling cycle no seal problems are there, while in GM cycle sometimes you may have sealing problems. But this sealing is very important, because it will not leave this low pressure gas to go to the low temperature gas to go to higher temperature gas or vice versa otherwise it will cool the cooling effect basically.

So, at low frequencies the rubbing seal between the displacer and the cylinder is perfect, it is designed in such a way that this remains perfect. The valves facilitates production of any kind of pressure wave as per the requirement system. So, here we had a sinusoidal motion Stirling cooler, we had a sinusoidal pressure and as I just talked earlier with usage of such a rotary valve, I can have any kind of pressure wave which I feel as optimum for giving me low temperature in a GM cooler. So, rotary valve could be designed in such a way that I can have a pressure pulse which you know takes so much time to go up to high pressure. I can retain it at high pressure at whatever time I want in a cycle come down to low pressure and retain it at low pressure at for; whatever time I want so, I can play with the waveform that will be generated due to this rotary valve in a GM cooler.

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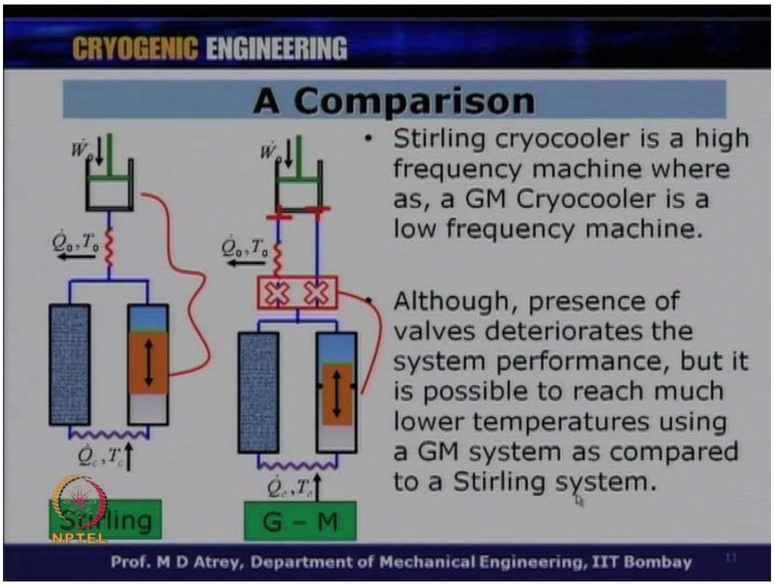

Stirling cryocooler is a high frequency machine this is what I talked about, this is a high pressure frequency machine and also the frequency of the piston is equal to the frequency of the displacer, while GM cooler it is a low frequency machine alright. Because we talked about having the seal, if this seal start moving at a very high frequency then, this rubbing seal will not function properly. And therefore, displacer works at a very low frequency of; let us say one to two hertz and that should be the again the frequency of the rotary valve. So, opening and closing of a rotary valve should also this frequency should be the same as what of a GM displacer in a GM cycle cryocooler.

Although presence of valves deteriorates the system performance always, whenever the valves come into picture you are going to have essentially a lot of pressure drop across this valve. The opening and closing of this valve will have a lot of pressure drop and therefore, the system normally is an inefficient system as compared to that of Stirling cooler, this is a very important aspect. So, a system c o p or a g m cooler efficiency will be quite lase as compared to that of a Stirling cooler. But then it is possible to reach much lower temperature using a GM cooler as compared to Stirling cycle machine all right.

So, a two stage GM cooler can give me around four Kelvin temperature, while a two stage Stirling cycle may give me around 20 Kelvin temperature, that is the difference between these two systems a high frequency machine and the low frequency machine.

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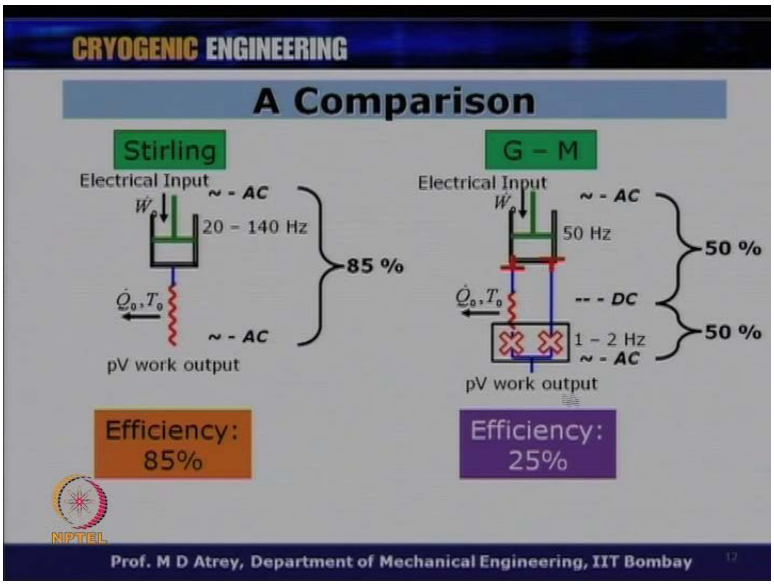

So, if I were to compare these two systems, I would like to show with a simple schematic over here and we can see that this is a Stirling cycle machine, where you got an electrical input and this electrical input is in AC form. That means, the voltage is fluctuating or this piston is going up and down and ultimately what I get output from this machine also is a pV work output which is also the pressure is oscillating. So, ultimately for any input which goes to the expander is going in the form of an alternative AC oscillating circuit basically, alternating current kind of a thing basically.

So, input is also alternating, while output also is alternating and there is no conversion from AC to DC or alternating current, let us say to a direct current. For example, so my input frequency around 20 to 140 hertz and the output also will be of the same frequency 20 to 150 hertz at whatever frequency the piston is oscillating. And therefore, in such a system where is; there is no change of AC to DC mode for example, your efficiencies are pretty high and this efficiency we can say as high, as 85 percent. We can assume 15 percent to be mechanical losses in a system because of friction etcetera.

If I were to compare this with a GM cryocooler, you can understand I am giving oscillating input over here. But then I have got a DC here, I have got a HP line, I have got a LP line, high pressure line and low pressure line, which we can compare with a DC direct current now, with no oscillations in this case. That means, whatever input has come to this piston, it has got from converted from AC to DC over here, after rotary valve what I get again is like, what I get here in a Stirling cooler oscillating pV mode that means, oscillating pressure which goes to expander. That means, I am converting this DC again to AC that means, there are two variations happening, two mode changes are happening AC to DC and DC to AC again.

So, this is what I am going to show here AC to DC and DC to AC again and if I assume that my conversion frequency from AC to DC is around 50 percent and again from DC to AC is 50 percent so, whatever is available is only 25 percent. So, if I give 100 watts input at this point only 25 watts are available to go to the expander, while in this case if I give 100 watts around 80 watts of pV power will go to the expander and that is the difference between these two cycles. A Stirling cycle therefore, is more efficient, because there is no transfer of modes from AC to DC or DC to AC, it is all AC to AC while in this case GM cooler, you convert first the oscillating motion to oscillating pressures to steady pressures no changes.

And again you convert these steady pressures to oscillating pressures, if we assumed the efficiency to be 50 percent for each conversion, what you get ultimately is only 25 watts if I supply 100 watts here. That means, it shows the inefficiency of a system is very high, the inherent efficiency of a GM cycle is very very low in this case.

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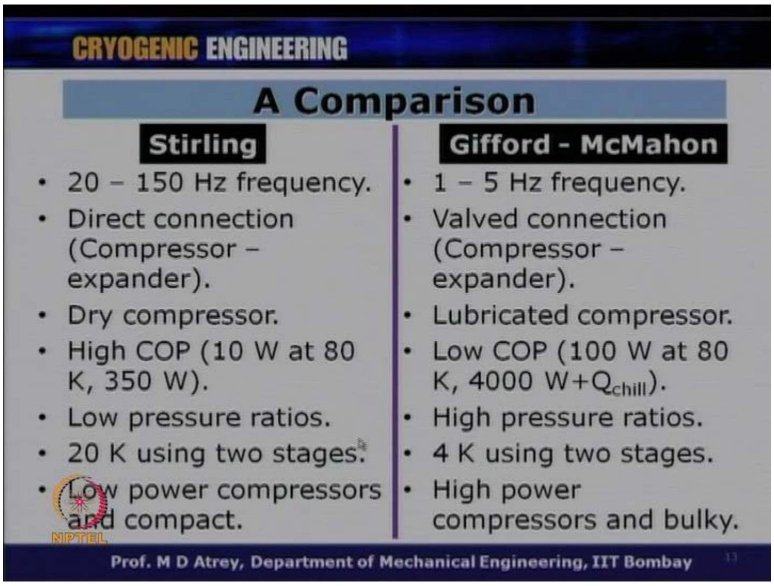

So, I just want to compare in short a Stirling cycle with a Gifford-McMahon cycle, I have explained all these things, a Stirling cycle is a high frequency machine of around 20 to 150 hertz, while a Gifford-McMahon is 1 to 5 hertz now, low frequency machine. You have got a direct connection a compressor is directly connected to expander without having a valve, while you have got a valve connection between the compressor and expander which is what we talked about. Now, when you have got a compressor directly connect to expander, I cannot use any lubricant in the Stirling cycle compressor.

And therefore, it use lubrication-free compressor which is what we call as dry compressor, in Gifford-McMahon Cryocooler you have got a lubrication compressor which; therefore, there will be a oiled compressor and one has to take care of this oil, one has to separate this oil from the compressed gas. This oil should not go to the expander otherwise oil will get frozen. So, you have got a now kind of a filtering mechanism in a helium compressor that you use normally in a GM cryocooler, because of the efficient system, you have got a very high COP in this case. For example, I can get 10 watts of power cooling effect at 80 Kelvin, for a power input of around 300 and 50 watts.

While in Gifford-McMahon Cryocooler I get low COP, I can get only 100 watts of cooling effect at 80 Kelvin, for a power input of around four kilowatt plus chilled water whatever power goes for chilling water. So, I can say around one or two kilowatts additional. So, I get only 100 watts of cooling effect by giving almost 5 to 6 kilowatt power input in a GM cycle machine that means, it shows that the COP is pretty lased in this case as compared to that of Stirling. The pressure ratios are low in this case which is a disadvantage in Sitrling coolers, because they are directly connected to compressor to expander. I get low pressure ratio while, because I have got a valve, I have got higher pressure ratios in case of a GM cryocooler and because the system works again at low frequency.

Normally, I will get around 20 Kelvin using two stage in Stirling Cryocooler, while I can reach up to 4 Kelvin using two stages in a Gifford-McMahon Cryocooler again owing to the fact that I am basically having a valve in it unit. But I am do not forget that to get this 4 k equal, I am going to give lot of power input to the compressor, I am can give 5 to 6 kilowatts over here. So, normally in a Stirling cooler, I will have a low power cryocoolers and they could be very compact, while in GM cooler I will get high power compressor and they will be bulky basically.

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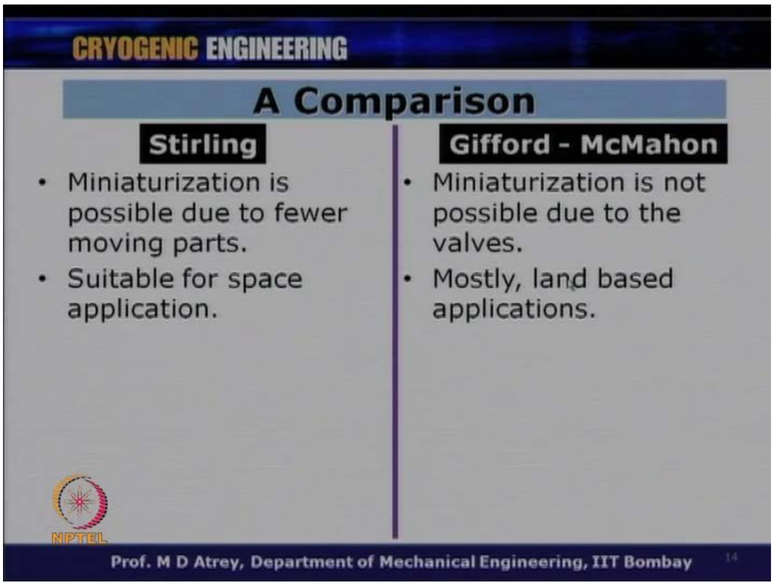

Normally in Stirling cycle cryocooler, because they use dry compressor, this facilitates to go for miniaturization and that is again because there no valves in the system. So, miniaturization is possible due to fewer moving parts, in this case because of the absence of valves in this case mostly while miniaturization is not possible normally in a GM cryocooler due to the presence of valve and therefore, less efficiency in this case. Mostly Stirling coolers are preferable for space applications, because they can be miniaturized and they are most reliable, as there are no valves in the system and the efficiency is or the COP of the system is pretty high. While here mostly the GM coolers are land-based applications only, because of the inefficiencies involved, because the reliabilities are questionable sometimes, because the servicing requirement that is required for a lubricated compressor alright.

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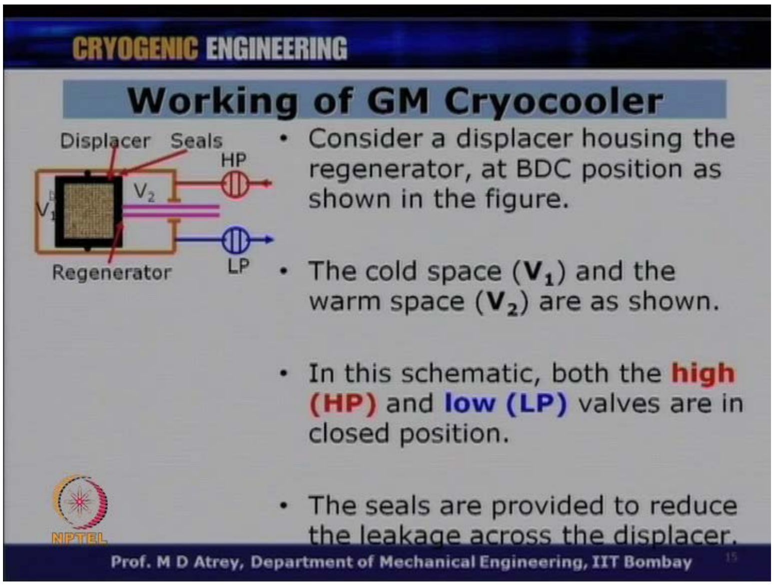

So, now let us see how the GM cryocooler works. So, let us see the working of a GM cryocooler, and what I am showing here is a cylinder which is housing the GM displacer and this GM displacer houses the regenerator. So, you have got a seal between the cylinder and the displacer, which is moving and the displacer is kind of hollow and in this we have got a regenerator material sitting over here alright. And this displacer will move up and down in this thing and there are valves high pressure and the low pressure valve, which open and close which generates the pressure wave.

So, consider a displacer housing, the regenerator at a bottom dead center BDC. So, displacer is at the bottom most portion and there is some gas actually the clearance volume the lowest volume that is possible in this cylinder. So, displacer is at a BDC position as shown in this figure and there are two volumes V 1 and V 2, V 1 is below the displacer, V 2 is above the displacer. So, cold space is going to be at V 1, we are going to create cold at this point. So, cold space V 1 and the warm space V 2 are as shown over here. Similarly, what we have is a high pressure valve called LP HP and LP in this schematic both the high pressure valve and the low pressure valve are in closed condition. So, I have got these two parallel lines shown they are opposing the flow and therefore, the high pressure gas is going to come from this side and this is right now in a closed condition, also this is shown to be in closed condition right now. And the seals are provided between the displacer and the cylinder as shown over here and this seal will not allow the gas from V 2 to go to V 1 or from V 1 to V 2.

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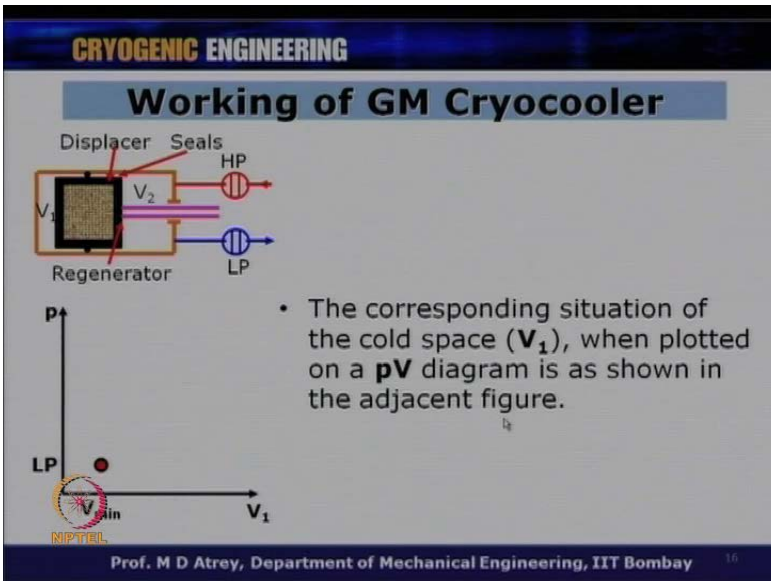

I would like to show now, what is how the pressure v, pressure versus volume diagram changes with this motion of displacer and we are talking about this volume V 1. So, at present we have got a v minimum this and the gas let us say at low pressure is there at V 1. So, corresponding situation of the cold space V 1 when plotted on a pV diagram is as shown in the adjacent figure, as shown over here.

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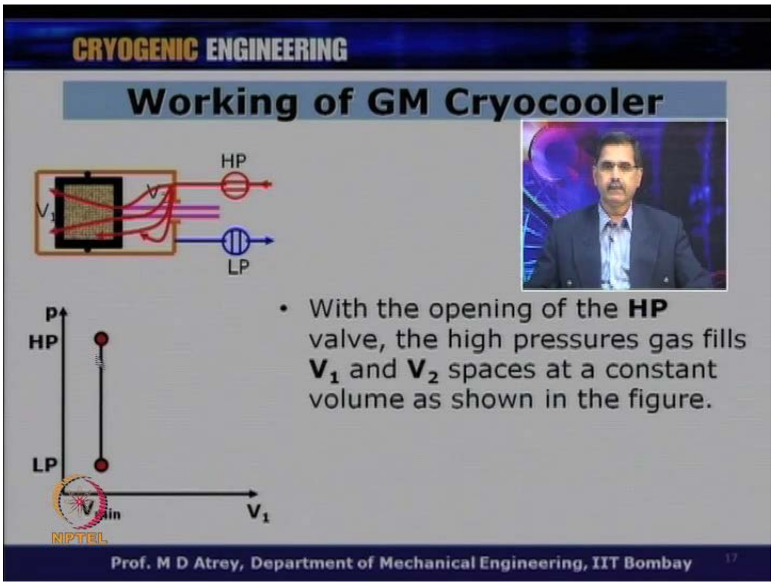

So, now you can see that I have made the high pressure gas open, I have made the HP valve open with the opening of this HP valve, the high pressure gas fills V 1 and V 2. So, high pressure will come from this gas and it will go through the displacer the regenerator and everything will be now filled up with high pressure gas. So, the gas is filled up with V 1 and V 2 spaces at constant volume and therefore, the V 1 pressure will suddenly go from LP to HP alright. It was initially assumed to be at LP, it will go to HP and therefore, the volume as v minimum only.

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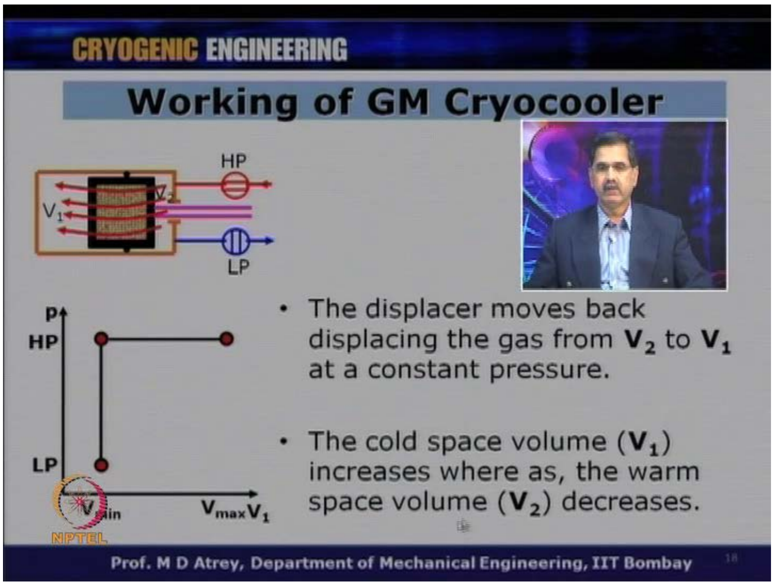

After some time the displacer will move on this side, the displacer moves back on right side and therefore, it will let the gas in the regenerator and the V 2 everything to move in V 1. What is (( )) therefore, going to happen to V 1, the V 1 volume will increase from V minimum to V maximum and during this time the high pressure is going to come from this side to this side, because of the motion of displacer. And therefore, the HP remains the same, the gas entirely remains at high pressure except that the V 1 volume; the volume in the V 1 increases from V minimum to V maximum at constant pressure.

The displacer moves back to the right side, it displaces the gas from V 2 there is some gas which is stored in the regenerator also is goes to V 1 at constant pressure, because the gas entirely is there at HP, because only HP is open right now. After that what happens, the HP will get open, will get closed and the LP valve will open. So, suddenly the high pressure gas in V 1, and even in V 2 and in regenerator suddenly will get exposed from high pressure to low pressure. So, what you can see now, the cold space V 1 in this case has increased from this to this, while the warm space V 2 has decreased.

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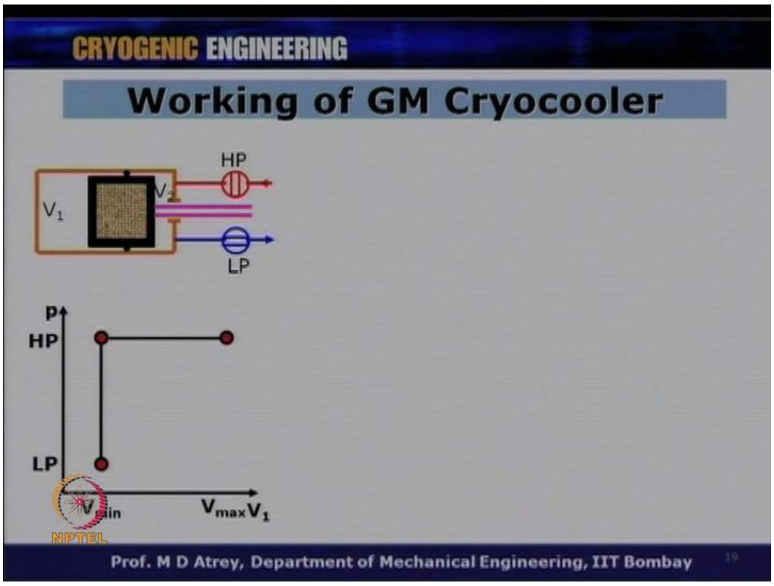

Now, the third thing is LP has opened, HP has remained in a closed condition the LP valve opens and now, the HP valve is closed and the LP valve is opened, this leads to an expansion of the gas. So, suddenly what was at high pressure, suddenly gets exposed to the low pressure therefore, what will happen the temperature will come down alright. The gas temperature here at V 1 will suddenly come down, this expansion produces the cold and now with the motion of this displacer later, as the displacer will move to it is left, the displacer moves back reducing the cold space volume.

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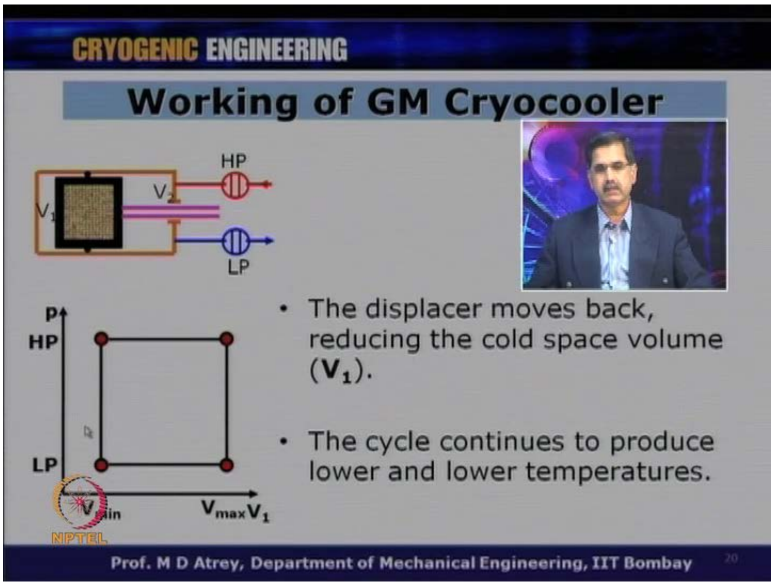

So, now when the displacer moves from this side to this side it goes to the minimum position, it will displace all the gas from here to come out on this side, the gas will go to the LP and the cycle will continue. So, we have come from first increase the pressure HP opens LP is closed, HP opens the pressure increases for V 1 then, displacer moves therefore, the V minimum goes to V maximum constant pressure line here. And then suddenly LP opens HP remains closed, expansion happens this is the period when we get low temperature generated at this point. And when the displacer moves to the left side, the gas will go out, the volume of the gas reduces from V max to V minimum and the cycle continues.

This cycle continues to produce lower and lower temperature and at particular temperature, it will get steadied down depending on the kind of regenerator action you will have. So, as soon as the regenerator cannot take more heat, it cannot store more heat the lowest temperature will be there and initially you will have unsteady state. That means, the temperature will go on lowering and at a particular temperature when the regenerator material gets saturated the lowest temperature can be achieved. This is how the GM cooler works very important that if I want to reach lower and lower temperature, I cannot attain this lower temperature in one stage, but I do multi staging. So, GM cooler is always known for it two stage machine, because it produces 10 Kelvin or a 4 Kelvin temperature.

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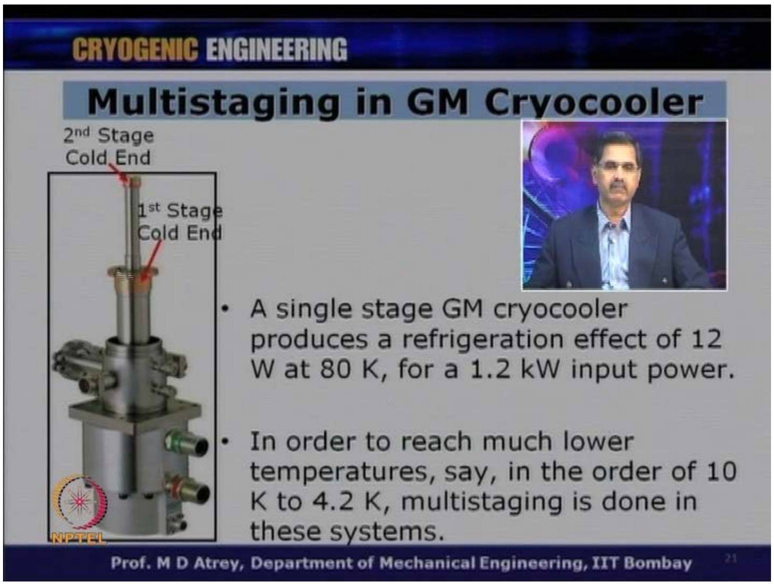

So, normally a single stage GM Cryocooler produces a refrigeration effect of around 12 watts at 80 Kelvin for a power input of around 1.2 kilowatt, these are some commercial figures available. So, I give 1.2 kilowatt input to the compressor what I get in effect is cooling effect of around 12 watts at 80 Kelvin. And then I will go for if I want to come down below 80 Kelvin or below low temperature, I will go for multi-stage or a two stage machine. So, this is the kind of a two stage machine you can see here and this is where you see the high pressure and low pressure gases coming from and they got a valve housed over here. This is the cylinder which houses a displacer which goes up and down, this is the first stage and the second stage.

This is a typical cold head a GM cold head, the compressor is going to be away from this place, but the high pressure line of the compressor will get attached to the high pressure port or valve here and the low pressure will come and it will get attached to the low pressure valve over here. So, in order to reach much lower temperature for example, to go to 10 Kelvin or to 4.2 Kelvin right of this order 10 Kelvin 4.2 Kelvin multi staging is done in this system. So, I will get 10 Kelvin or 4.2 Kelvin at this second stage, while the first stage could be around 40 to 50 Kelvin depending on the sizing of this particular cryocooler.

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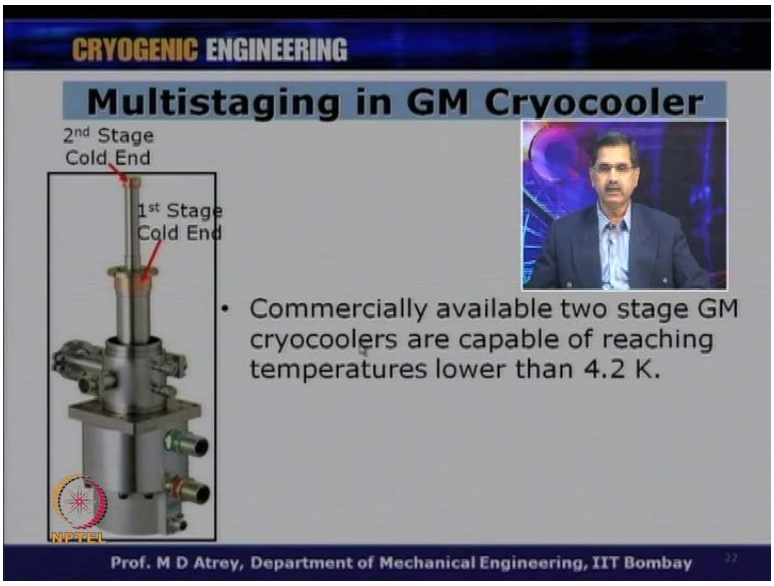

Commercially available two stage GM cryocoolers are capable of reaching temperatures lower than 4.2 Kelvin. In fact, the lowest temperature that could be reached could be around 2.4 to 4.5 Kelvin, but you need some cooling effect at 4.2 Kelvin.

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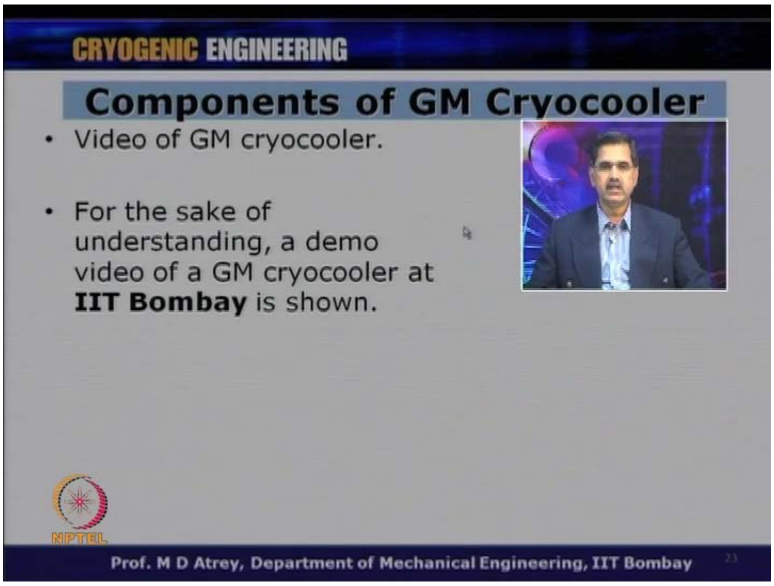

Now, let us see a video of a GM cryocooler that we have bought at IIT Bombay it is from a Libolt company and from that you can see an actual machine, I am not going to run this machine, but you can see different parts of these machines. So, just now, we saw this machine for the sake of understanding a demo video of GM cryocooler at IIT Bombay is just shown you. Just saw how does a compressor look what are this flex line, what is this cold head and you could see in video how are they placed, how do they look like, how does the sizing and thing like that.

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So, let us have a look at a GM cryocooler, Gifford-McMahon cryocooler and what you are seeing right now is a Gifford-McMahon cryocooler with a compressor at this place and the cold head or expander head at this end. Now, here you can see that the compressor is connected to the cold head using these flexible lines. And this is the compressor and you can see this compressor with a high pressure and low pressure line connected from this compressor. And this is helium compressor of around 8 kilowatt power capacity and this is also a power cord which connects the power to the valve, the rotary valve of the GM cryocooler all right.

This is a high pressure line, this is the low pressure line, this is where you can read the pressures this is the on and off switch of this compressor. And as you will see further that the gas will get compressed from here, the gas will go from here to cold end and the low pressure gas will come back to the compressor and to the capsule inside and a water cooling arrangement. Now, what you also see from here is a water cooling arrangement, the water will go as inlet, water will come outlet from this, it will go to the chiller and again the water will enter from this place, cold water will take the heat of compression from this place. It will enter, it will take the heat of compression, it will come as hot water from this and it will again go back to the chiller and it will come back again from this particular port.

This compressor is normally a three phase, it has a three phase power supply what you see is a Libolt compressor. Now, here or a Libolt GM cryocooler and these are the flexible lines of around six to eight meter length, it could be 20 meter also in order that compressor could be kept as much away from the cold head.

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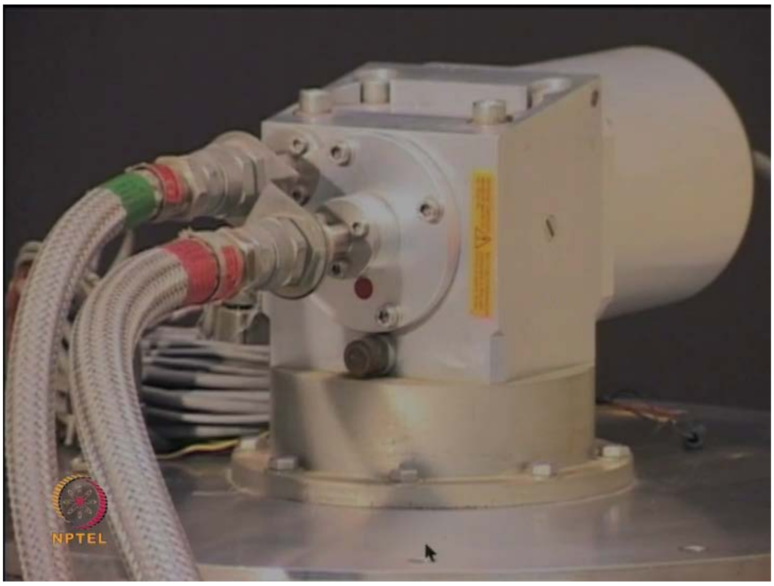

Now, come to this point and what you see here is a cold head now, from where you can see that the high pressure line comes from here, the low pressure line will take the gas from here. What you see now is a valve, the rotary valve, this particular housing has the rotary valve, the high pressure gas comes inside there is a rotary valve, which is housed in this and this is a motor which is driving this rotary valve. And the power supply to this motor comes from the compressor and that also one can see that it should run at one hertz or two hertz that also can be decided by the input that can be given on the compressor.

So, here this housing has the rotary valve which is driven by this motor, we have seen how this rotary valve works. So, for some time, the rotary valve will allow the high pressure gas to go from here to the cold head and the low pressure gas will go, will leave this place through this port and it will go to the compressor to get charged again, to get compressed again alright. So, now what you see below this flange, this is the cold head which is connected to this flange and this flange will sit on the vacuum vessel which I will show you later.

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So, this is the cold head now, this is the first stage and this is the second stage of the GM cryocooler. Now, this is a 10 k cryocooler so, I get around lowest temperature of the order of the 8 to 10 Kelvin at this point which is the second stage and I get the first stage temperature of around 30 to 35 Kelvin at the first stage at this point. This houses the displacer, two stage displacer driven by the motor which is kept or it can possibly get driven by itself .If you have got a pressure drop across the displacer and this is called as free displacer in that case. The displacer will go up and down with the frequency that you maintain as 1 hertz or 2 hertz and displacer also houses the regenerator.

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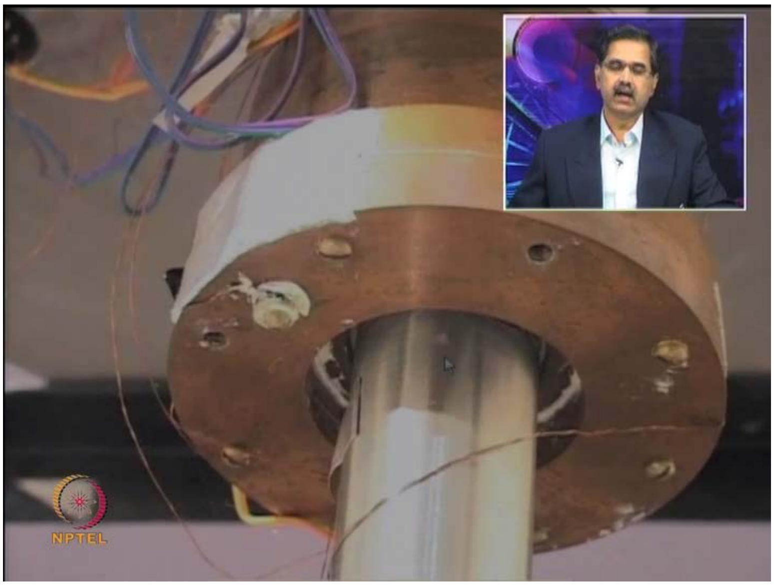

This is the second stage, this is the first stage here and what you see here is the first stage and what you see here also is a silicon diode which has been kept here to measure the temperature at this particular point. We can measure the first stage temperature at this point and similarly, we have got a two stage now, you can see this flange over which is copper. So, anything if I want to connect anything to be cooled by the first stage can be connected to this different holes or this could serve as a radiation shield for the second stage one can put a radiation shield across this second stage. The entire thing has to go under vacuum so that there is no 300 Kelvin radiation that is coming or you do not have air around this all right.

So, you can see that above this what you have got is a first stage regenerator, below this in the displacer housed is the second stage regenerator which normally will have, because it is a 10 k cryocooler. It will had lead balls as the regenerator material, while the first stage will have stainless steel mesh as a first stage regenerative material. What you see also the circuit of the first stage and the second stage silicon diode in order to measure the temperature now, this is the second stage.

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So, here in the second stage whatever you want to cool will be conductively coupled in the second stage of the GM cryocooler.

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Now, if I want to test the performance of the GM cryocooler, we have made this vacuum jacket and in this vacuum jacket this two stage GM cryocooler will be put in. So, this flange can be taken off and the flange with GM cryocooler can be put in this case. So, this is basically about a vacuum jacket to test the performance of GM cryocooler.

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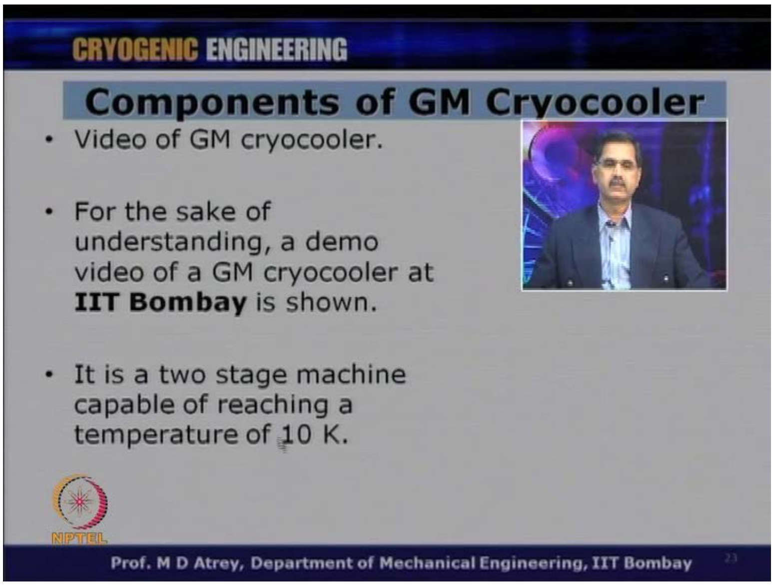

It is a two stage machine which is capable of reaching a temperature of around 10 Kelvin, the lowest temperature possible is around 10 Kelvin, but normally it is referred to as 10 Kelvin cryocooler, 10 Kelvin machine.

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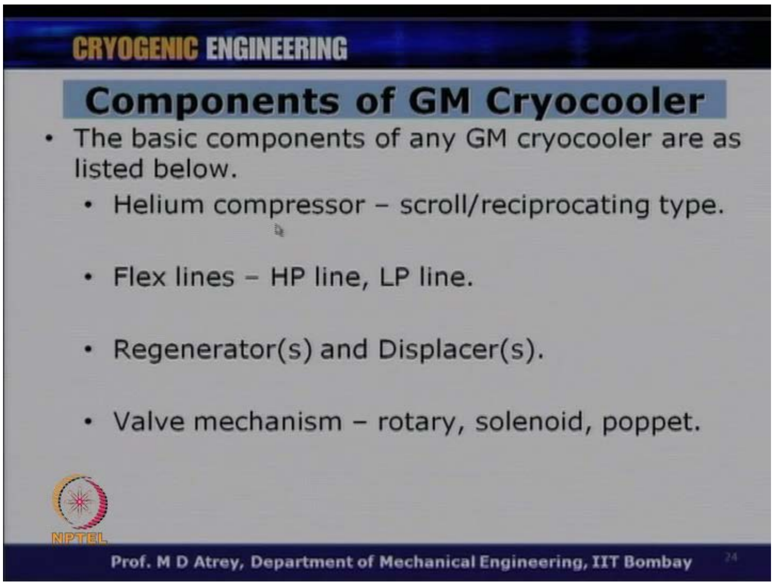

So, what are the different components of a GM cryocoolers, the basic components of any GM cryocooler as are as listed below, it has got a helium compressor the working fluid is normally helium. And therefore, it will have a helium compressor which could be a scroll type, a screw type or a reciprocating type normally; it is a scroll type machine basically. Then, we have got a flex line and this is what we call as flexible line actually, the short form given as flex lines and we have got a HP line and LP line. In order to keep the compressor away from the expander or the cold head, this flex line could be 6 meter length or could be 20 meter lines. So, that means, compressors vibrations will not reach the cold head, in some case the cold head vibrations are very very detrimental.

For example, on AMRI machine, where this system sits the compressor is kept outside of the building in fact, so that there is no noise, there are no vibration transferred to the cold head. So, the flex line does the purpose that it will allow the high pressure gas to come from the compressor and to come to the cold head. Then of course, the regenerator and the displacer, the regenerator as we just saw is housed in the displacer and is a very important component is the regenerator, which has got regenerator materials sitting there. As a regenerator matrix which play a very important role in the functioning of any cryocooler. In the next lectures, I will show what these regenerator materials and everything look like, but for the time being we will just go ahead with theory.

As we are talking about every time this valve mechanism, the rotary valve mechanism it could be solenoid valve it could be poppet valve, this is the most important thing. And therefore, a GM cooler will have a helium compressor, flex line, the regenerator, displacer with a cold head for example, and the valve mechanism, these are very important aspects of a GM cryocooler.

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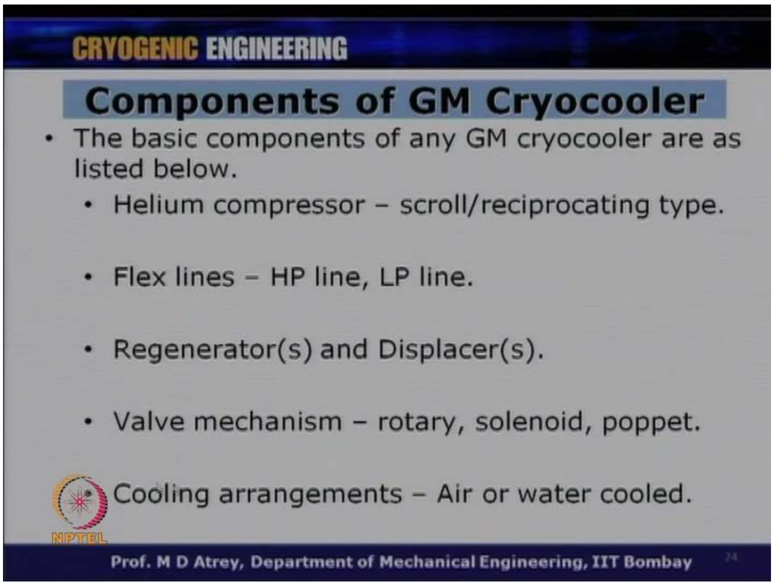

Finally, we have the cooling arrangement for helium compressor the heat of compression has to be taken car by this cooling arrangement. Normally it is a chilled water and chilled water at around 8 degree centigrade or 15 degree centigrade will inlet; will be inlet to the helium compressor and it will take the heat and go back, it will get cooled and again come back. So, basically it is normally chilled water, as we meant sometimes it could be air cooled also, some compressors are air cooled also and therefore, it is very important what kind of arrangement has been made over here for compressor cooling. Now, let us come to the regenerators of a cryocooler, the regenerator is the most vital component and is often called as heart of the cryocooler.

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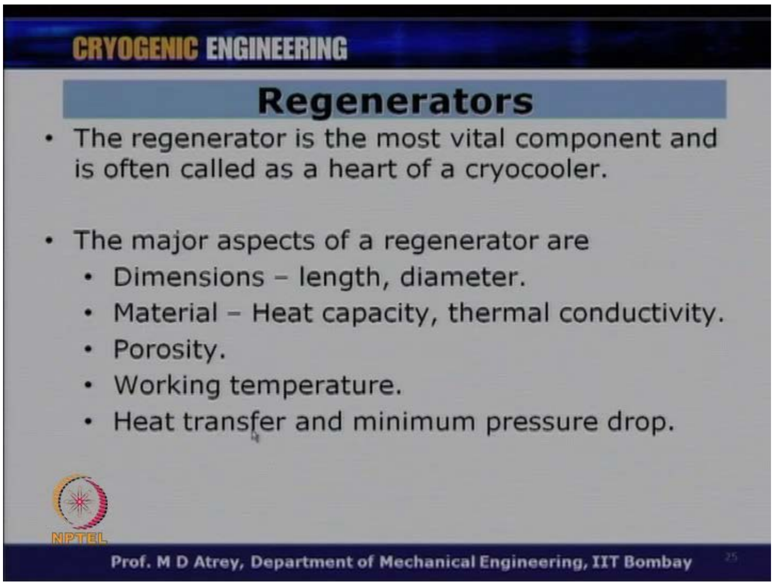

So, entire design of a cryocooler will basically depend on the regenerating capacity, what does the regenerator do? The regenerator stores the heat and therefore, everything depends on the storing capacity of heat by the regenerator. What is the storing capacity is m is the mass of the regenerator into CP, the specific heat capacity of the regenerator material. The regenerator houses the material and through this material the gas flows that means, the regenerator has to have some porosity. The regenerator has to allow this gas to pass to this material and in such a way that there will be very good heat transfer between the gas or the working fluid and the material that are stored as regenerator matrix.

So, the major design aspect I will say, the major aspects of the regenerator therefore, are the dimensions the length and diameter. So, regenerator dimension makes a very important impact on the functioning of a cryocooler, depending on what kind of compressor what kilowatt compressor you are using. That means, how much is the flow rate of the machine in comparison to that we have to have a capacity of the regenerator, which are determined by the length and the diameter of the regenerator alright. So, our regenerator material will be housed in these dimensions, it will have it is volume and this regenerator matrix should be able to take the heat given by this gas, during it is travel through this regenerator. And therefore, the dimension of the regenerator, you have to calculate very very critical.

The material, what material you choose because the material is a very important, this is the material which stores heat. So, it is heat capacity variation with temperature because you are going to work at low temperature and we have seen in the materials earlier that the heat capacity goes on reducing as the temperature gets reduced. Therefore, you have to choose such a material, which has got higher heat capacity at low temperature. Comparatively high heat capacity at low temperature also the thermal conductivity of this material also is important, because this is what will determine the diffusivity of the material also all right.

So, they are very important thermo physical of the material that has to be used as regenerator matrix material. It has to have very high heat capacity at low temperature in comparison with the heat capacity of the gas which is flowing through this. So, we should say that the ratio of heat capacity of matrix to that of gas will be infinite basically in order to have a very good heat transfer alright. So, this going to decide what is the lowest temperature that could be attained by this cryocooler. Because at that particular temperature the regenerator will get saturated that means, it cannot take any anymore heat from the gas the matrix gets saturated. So, the; this is a very important aspect of the regenerator.

As I said, the gas the working fluid travels through this matrix material and therefore, it has to have some porosity. And this porosity allows the gas to travel through this matrix material it also allows to have a good heat transfer between the gas and the matrix material. So, we need to have a good porosity, an optimum porosity through this material, what is the working temperature, what is my working temperature range. I am talking about, am I talking about 30 Kelvin machine, am I talking about 10 Kelvin machine, am I talking about 4 Kelvin cryocooler according to which the material will change so, working temperature will decide the material. So, if I want to have a cryocooler working around 30, 40 Kelvin I will use stainless steel mesh, while if I want to work at very low temperature, I can go for lead balls or magnetic materials. I will talk about that in next slide.

This is what I talked about, the heat transfer between the working fluid and the material has to be perfect, but you know that when you got to have a perfect heat transfer you will have more pressure drop. So, I want is perfect heat transfer at the same time I would like to have a minimum pressure drop and therefore, one has to play between this porosity and the sizing of this matrix material. This is a very important aspect I would like to have maximum heat transfer and minimum pressure drop in the regenerator alright. Because regenerator has got some porosity it will have a good heat transfer, but the moment it has less porosity it will have a high pressure drop and this is very important aspect.

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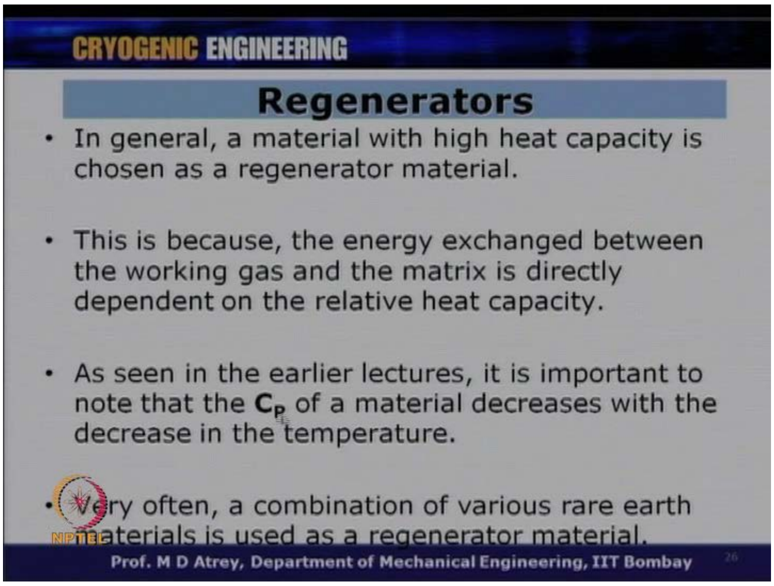

So, the regenerators in general, the material with I just told you, with high heat capacity is chosen as regenerator material. This is because, the energy exchanged between the working gas and the matrix is directly dependent on the relative heat capacity. As I just said that, the heat capacity of the matrix material should be infinitely as much as high as possible, it should be as high as possible as that of the heat capacity of the gas. As seen in the earlier lectures, it is important to note that the Cp of the; this is specific heat capacity of the material decreases with the decrease in temperature alright. In certain cases it comes very close to zero even and therefore, such materials need not be used as regenerator material in this case.

Very often, a combination of various rare earth materials or the magnetic material which we call as is used in the regenerator material, because they show very high heat capacity at low temperature. They may not normally have very high capacity, but at low temperature they show a transition and suddenly the Cp value increases and this particular property of magnetic material is exploited in this regenerator. For example, here I am going to show you some regenerator material at temperature less than 50 Kelvin.

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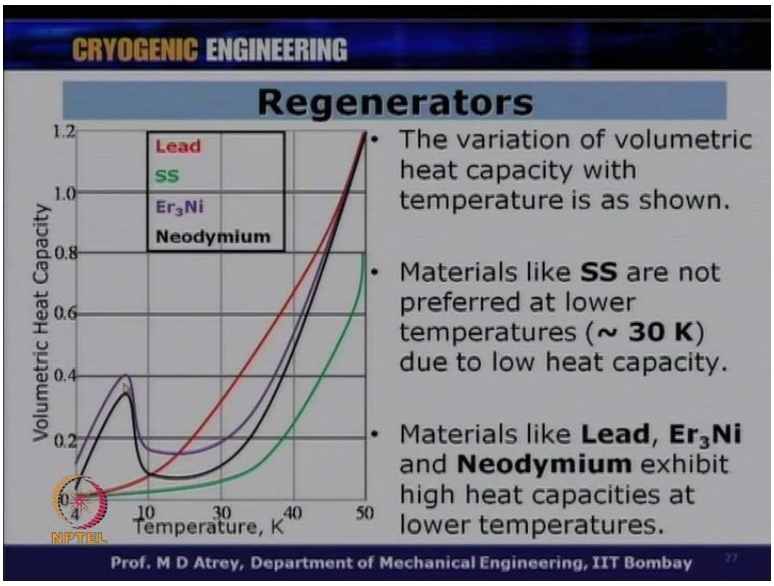

So, we are talking about let us say stainless steel and this is a green, this is Cp value and we are talking about volumetric heat capacity alright. So, volumetric heat capacity is going to come down below 50 Kelvin and therefore, it cannot be used below let us say 30 Kelvin. Till 30 to 40 Kelvin I can use stainless steel and normally the stainless steel material is such that it can be made in the form of meshes. That means, the gas can flow these meshes thereby having a good heat transfer between the gas and the stainless steel mesh. So, here we are seeing the variation of volumetric heat capacity with temperature as shown, the material like SS are not preferred at lower temperature, let us say less 30 Kelvin due to low heat capacity.

So, what do I do, I during; if I want to have a 10 Kelvin machine for example, from here we can see that I got a lead over here. And this lead can be used because it has got substantially higher heat capacity as compared to that of stainless steel below, let us say 50 Kelvin. So, normally if I want to come and reach down to 10 to 15 Kelvin, I normally will use lead. So, I can have stainless steel in the first stage and I can use lead in the second stage as regenerator material agreed, it is a very important aspect. So, material like lead can be used for second stage if I want to reach 10 Kelvin, but what happens if I want to reach 4 Kelvin? I cannot use lead anymore I cannot use stainless steel anymore.

But, we can see these two curves having high Cp variation and this is what I talked about these are all rare earth materials or magnetic materials. And this erbium three nickel and neodymium for example, these materials have got low Cp, let us say to 10 Kelvin, but suddenly below 8 Kelvin this is a transition and this is called as transition of second order. Suddenly this transition goes up and the Cp value goes up and this Cp now is comparably quite high as compared to that of lead and stainless steel. And this property is exploited in a second stage of the regenerator for a cryocooler, for any cryocooler in order to reach around 4 Kelvin and temperatures below it.

So, materials like lead Erbium 3 nickel, Neodymium what we have not shown is Holmium copper all these materials can be used at low temperature, because they exhibit high heat capacity at low temperature. However, these materials cannot be made into the form of meshes like lead. The lead Erbium 3 nickel, Neodymium are normally made in the spherical forms, they are in a ball forms of around of around 0.2 to 0.1 millimeter diameter and this is what it is used in the regenerator for the second stages.

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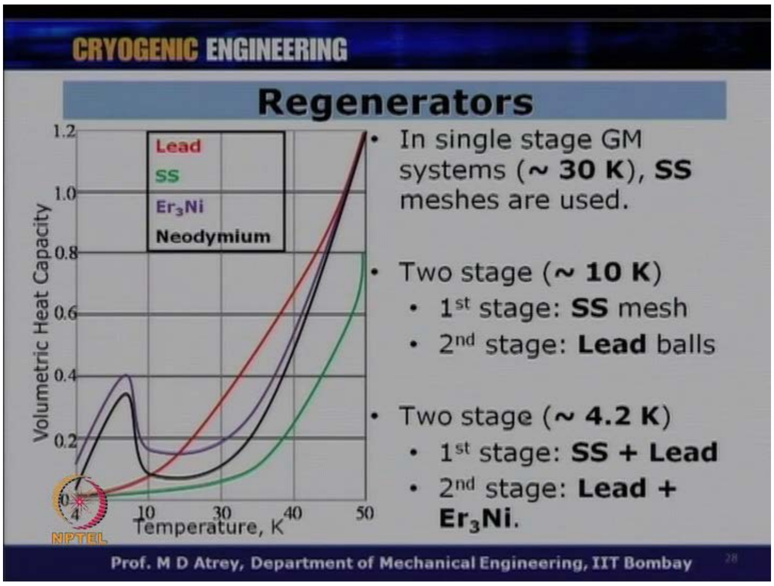

So, in a single stage, normally in a GM system stainless steel meshes are used in two stages let us say around 10 Kelvin, we will have first stage stainless steel mesh second stage lead balls. If I want to have a 4.2 Kelvin temperature or a 4 k machine, we can have first stage, we can have stainless steel plus lead in the first stage it is something referred as hybrid regenerator and second stage, we can have lead plus Erbium 3 nickel. And this is very important that how much stainless steel should be there how much lead should be there, how much lead and Erbium 3 nickel should be there these are very important design aspect of regenerator.

And lot of computational fluid dynamics is normally used to understand how this regenerator would play a role in determining the lowest temperature that could be generated by this cryocoolers. The third important aspect which I had touched was the valve mechanism. So, we talked about regenerator material, we talked about the Gifford-McMahon Cryocooler functioning and let us see now in brief, the valve which is a very very important component of the GM cryocooler. What does this valve do as I told you earlier the valve generates, the kind of pressure pulse I want. The valve basically will determine for how much time it should take to reach maximum pressure for how much time the maximum pressure should remain constant. How much time it should take to come down and from maximum pressure to low pressure and for how much time the low pressure should remain all these things are taken care by the valve mechanism or therefore, the valve design is very very critical.

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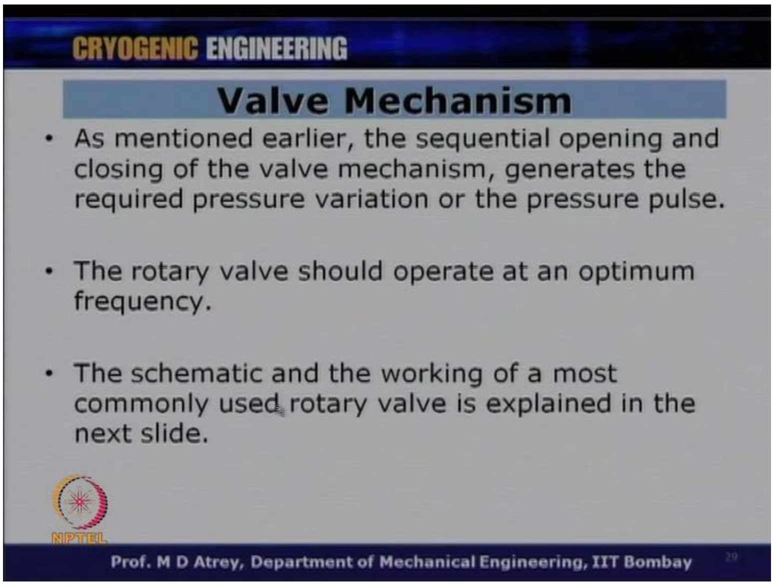

As mentioned earlier, the sequential opening and closing of the valve mechanism, generates the required pressure variation or the pressure pulse. The rotary valve should operate at an optimum frequency. We have seen that the GM cooler functions at 1 to 2 hertz or 1 to 3 hertz. Let us say this optimum frequency's very important at what frequency it should 1.5 hertz 1.4 hertz, this is what bow lot of people would even work at. So, one has to find out what is this optimum frequency and this will be; that will be decided by the pressure pulse that this valve will generate and of course, what is my cold head volume, what is my first stage volume second stage volume and thing like that various aspects. The schematic and the working of most commonly used rotary valve is explained in the next slide.

So, just for example, lot of papers have published how these rotary valves work and from one paper we have taken and, but lot of people will not even reveal how these valves work in those cases, because this is a very important commercial secrets. But as far as some published information is available, we have tried to transfer this knowledge to you, just to understand how does a simple rotary valve work.

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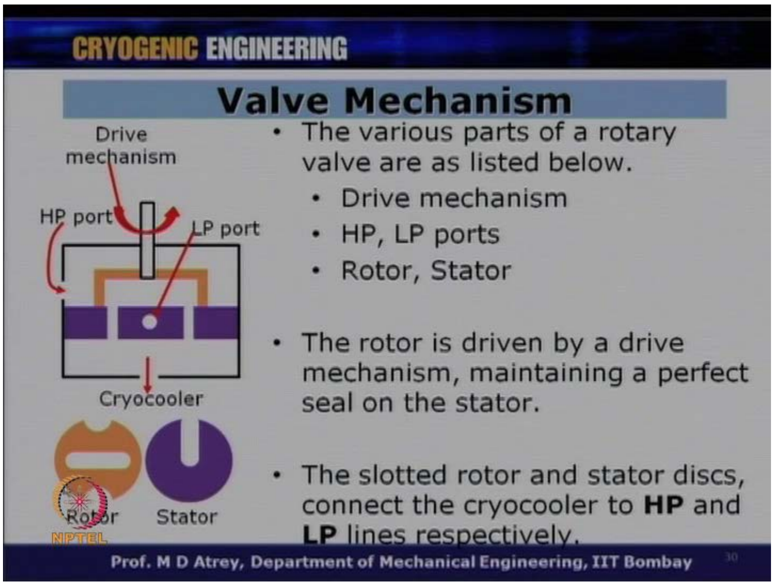

So, this is what a just a schematic of a rotary valve, the various parts of a rotary valve are as shown over here. So, you have got a rotary mechanism and therefore, dry mechanism this could be a motor basically driving this valve unit. So, let us say this is a valve unit and the gas, high pressure gas will come from some side, the low pressure gas will come from other side and ultimately what you get from here is a pressure pulse and this is going to; go to the cold head. So, what you see here is a drive mechanism, what you see is a high pressure and a low pressure port. So, you have got a high pressure gas which is coming like this and low pressure gas which is going into this plane, into the plane of this board basically.

So, you have got a low pressure valve opening somewhere over there, what you have got a Rotor and Stator. So, a rotor is as shown over here this rotor is getting rotary motion from this motor which is shown over here and you have got a stator. So, as you see a rotor is good in rotating while stator is going to be remaining stationary. And this rotor and stator are hard-pressed on each other (( )) and this is most important thing they should be hard-pressed. And therefore, you will have some spring loaded directly on them, I have not shown the schematics of that, but it should be ensure that this Rotor and Stator are absolutely pressed hard against each other.

The rotor is driven by a drive mechanism, maintaining a perfect seal in a system that means this rotor and stator. Because they are going to be; you know, pressed hard against them they will not leak and I mean, the high pressure gas and low pressure gas should not get leaked again in this alright. So, this is very important and we can see that there are special slots are cut on the rotor and the stator. The slotted rotor and the stator discs connect the cryocooler to HP and LP lines respectively, this is very important now. This curvature how long this is, what is at what angle this happens this is what is going to decide how much time it takes to increase the pressure and decrease the pressure. And how much time it should be kept at; what is the diameter of this all these will decide pressure pulse mechanism all right.

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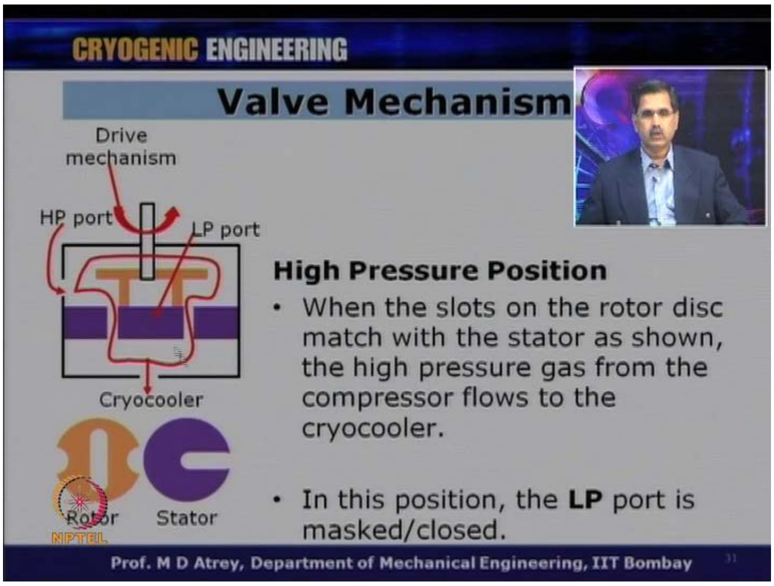

So, let us see now, the high pressure position is something like this, you can see the slotted mechanism and this is the port which goes to the cryocooler. And high pressure gas has opened and suddenly the disc has taken this position, because of which these two openings are open. So, this entire area over here is getting filled with high pressure gas and the gas now travels from this to these two openings, which is these two openings are meant open to the high pressure gas, because of the motion of the rotor. The rotor has moved in such a way that these ports the cryocooler got in touch with the high pressure and therefore, high pressure gas has moved through these ports and will go to the cryocooler..

So, I mean the slots of the rotor disc match with the stator as shown, the high pressure gas from the compressor flows to the cryocooler. In this way the high pressure gas will go to the cryocooler.

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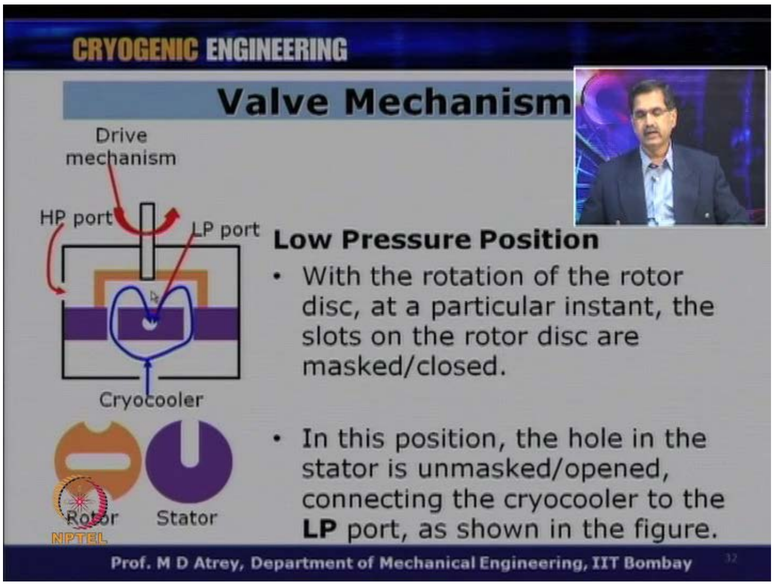

In this position the low pressure is completely closed to this gas, the gas cannot see this low pressure gas at all and when the position comes like this. Now, the low pressure position gets opened and the gas which travel now from cryocooler to the compressor. And this gas will come like that this port is not anymore opened to the high pressure side basically. So, entire area as I said was open earlier to the high pressure side now, suddenly low pressure gas will come like come like that and it will enter this hole, which is connected through this hole to the LP port of the cycle. Spend some time to understand this drawing basically, but I am just going to show you some schematic.

With the rotation of the rotor disc, at a particular instant, the slots on the rotor disc are masked and getting closed. Now, in this position, the hole in the stator is unmasked it gets opened, and therefore, this open gets opened it goes to this it gets; it connects now cryocooler to the LP port, as shown in this figure. And therefore, now the LP gets opened it goes here, it gets connected after some time, again the rotor gets opened the high pressure gas will come, again this position will come and the cycle continues. This is schematically very simple for me to possibly explain, but it is not very very simple to fabricate and demonstrate them in practice.

Because many times, you can find that it could be now, you have got a high pressure over here you have got a low pressure here. And there could be some clearance there, could be some leakage past this if the rotor and stator are not very very hard pressed over here. This is a very important aspect otherwise the gas can get short-circuited, the HP can get in touch with LP and the gas can just flow like, this is very important. Therefore, this should ensure that the rotor and stator are absolutely leak-tight there is no; they are hard pressed against each other. Coming finally, to the applications of GM cryocooler, what we have seen is, what is a GM cooler how does it compare with Stirling cycle, what we saw after that is also how does a GM cryocooler function.

Then, we also saw what are the important aspects of a regenerator in a GM cryocooler, which we also saw that for a multi-staging how do we go for low temperature and with respect to multi-staged temperature, two staged temperature how does the regenerator matrix material change. We just touched upon lastly the valve mechanism the importance of a rotary valve, the rotor and the stator and how do they function. And ultimately just to complete the task related to GM cooler, where do we apply where do we find applications of the GM cryocoolers. GM cryocooler has got tremendous application in fact, GM coolers have made cryogenics very very popular or to reach commercial destinations.

So, GM cyrocoolers find application in the following area MRI machine, every MRI machine is having a GM cryocooler sitting on it, which does the functioning of shield cooling many times or even recondensing cryocoolers. So, MRI machine is a very important area where GM cryocoolers find it is application.

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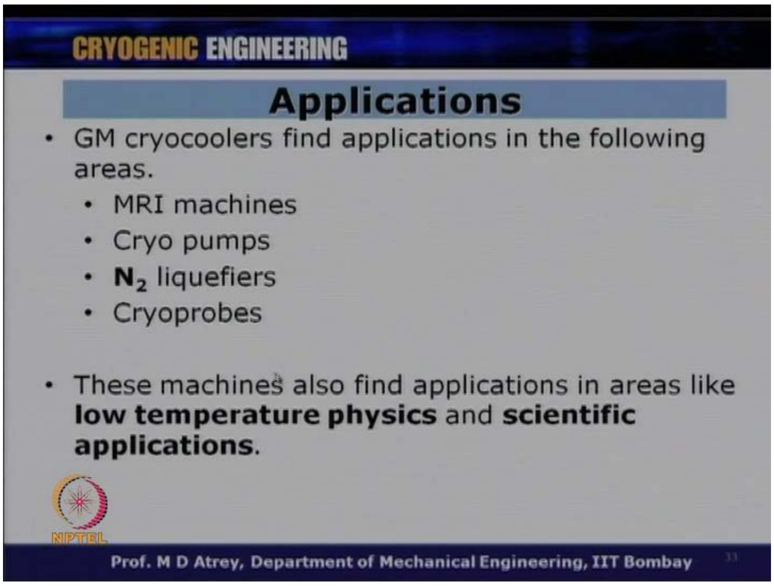

Cryo pumps so, all these cryo pumps which produce clean vacuum houses a GM cryocooler a 10 k GM cryocooler basically, which produces clean vacuum for various mems laboratories or microelectronics laboratories and thing like that. Nitrogen liquefier a single stage cryocooler can be used to produce nitrogen liquid nitrogen basically. So, this is very important application again cryoprobes so, quite a lot of NMR cryostats use cryoprobes to cool the electronics so that to increase the signal to noise ratio. And therefore, very popular equipment for NMR used is a cryoprobe, or a cold probe basically to get a very high signal to noise ratio.

These are some very important area where cryocoolers are needed in almost you know 100s and 200s and thing like that they are now, in 1000s for MRI machine example. So, very important 1000 for MRI machine maybe 10,000 for cryo pumps and thing like that. So, very important area GM cryocooler normally finds applications in. These machines also find applications for very low temperature physics and scientific applications. So, very important r and d application r and d group who want to do experiments at low temperature using GM cryocoolers.

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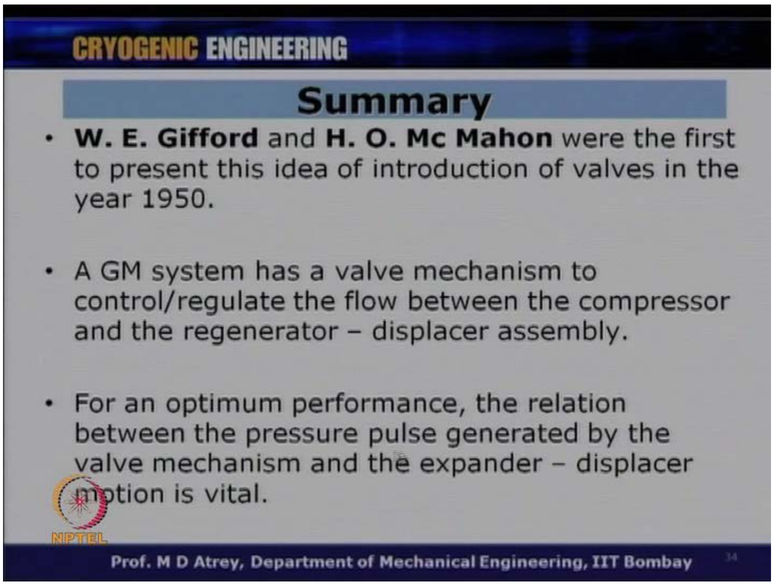

Summarizing Gifford and McMahon were the first to present the idea of introduction of valves in 1950. A GM system has a wall mechanism to control/regulate the flow between the compressor and the regenerator-displacer assembly. For optimum performance the relation between the pressure pulse generated by the valve mechanism and expander-displacer is vital.

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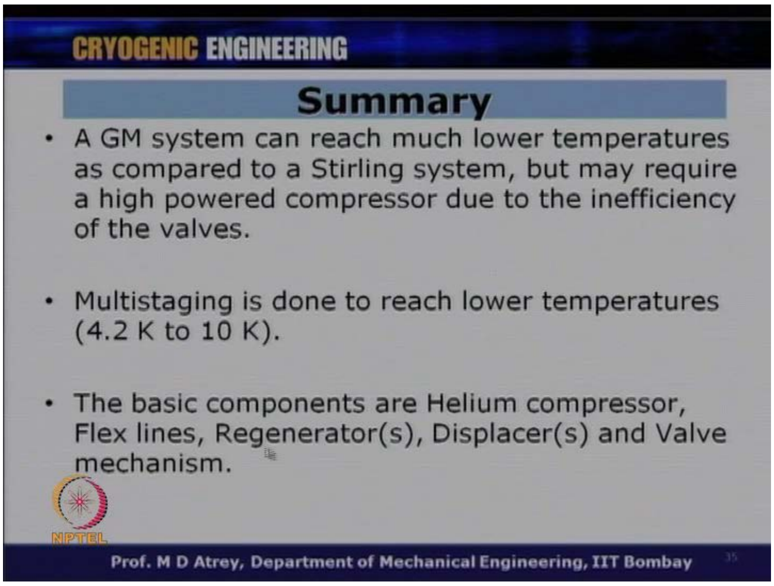

A GM system can reach much lower temperatures as compared to Stirling system, but may require a high powered compressor due to the inefficiency of the valves. Multi-staging is done to reach lower and lower temperatures you can get less than 4.2 Kelvin or a 10 Kelvin system whatever you want. The basic components of a GM cryocooler are Helium compressor, Flex lines regenerators and displacer valve mechanism etcetera.

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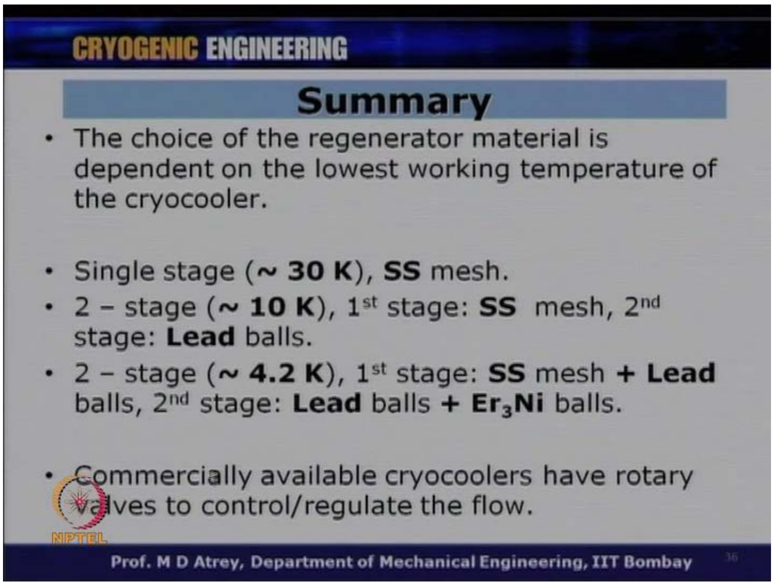

The choice of regenerator material is dependent on the lowest working temperature of the cryocooler. So, if I want to have a single-stage machine to reach 30 Kelvin I can used stainless steel mesh as the regenerator matrix material. If I want to go to two-stage a 10 k machine, I can have 1st stage with SS mesh and 2nd stage may have Lead balls of spherical nature. If I want to go to a 2-stage machine reaching around 4.2 Kelvin, the first stage could be stainless steel mesh plus Lead balls, second stage could be Lead balls plus Erbium 3 Nickel. This is just a guideline; it could be 100 percent stainless steel mesh also while 2-stage can have lead balls plus Erbium 3 Nickel. So, it is left to the design of a regenerator for that particular application. Finally, commercially available cryocoolers have rotary valves to control or regulate the flow, and this is the rotary valve is the moving component, which is a very important design aspect of a GM cryocooler.

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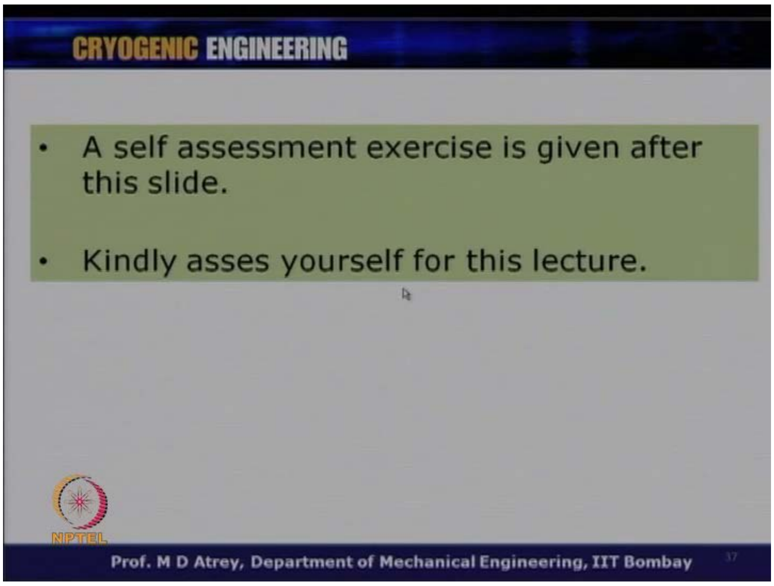

Finally, I have got a self-assessment exercise given, please go through that kindly assess yourself for this lecture alright. And we have given some answers at the end.

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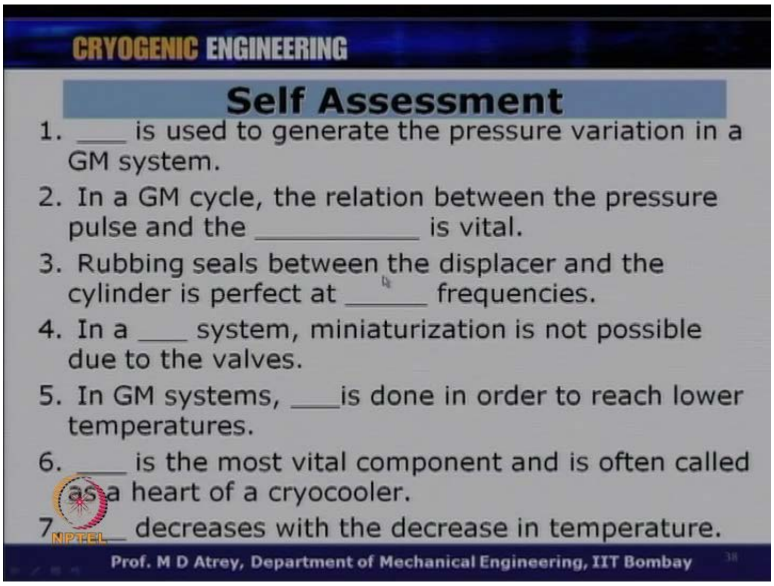

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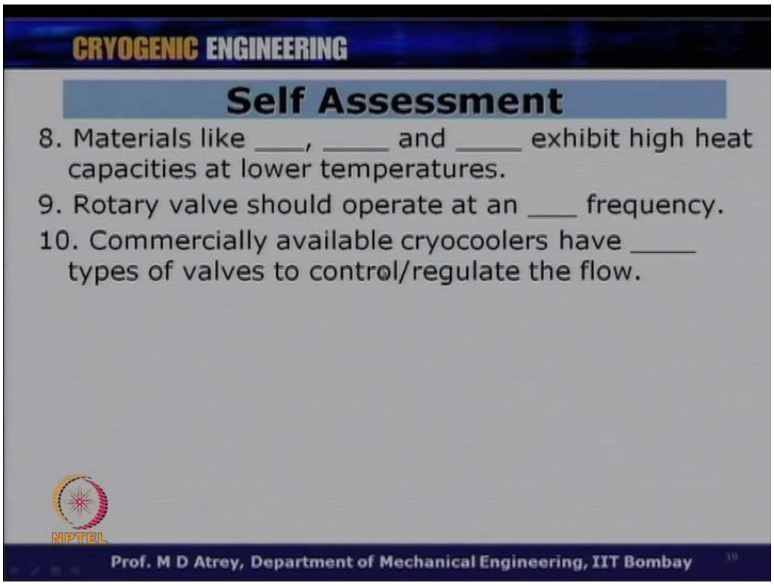

So, please assess yourself and see how much questions you can answer.

Thank you very much.