Cryogenic Engineering

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Lecture No. # 32
Cryocoolers

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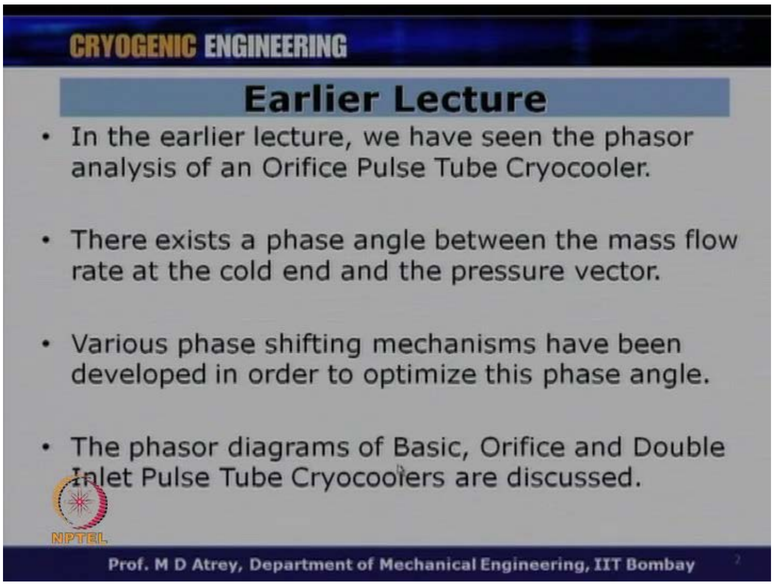

So, welcome to the 32 lecture on cryogenic engineering, under the NPTEL program. Just to see what we have done in the last lecture, we had seen that the phasor Analysis for the OPTC. Let also seen for the DIPTC, the phasor analysis. And we know that, there exist a phase angle between the mass flow rate at the cold end, and the pressure vector which is the costitized responsible for increase in the cooling effect. And we had said that this cos theta has to be maximum, in order that cooling effect is maximum. And in order to make this cos theta maximum; that means, theta to be smaller, we employ various phase shift mechanisms to the pulse tube cryocooler.

So, various phase shifting mechanisms have been developed in order to optimize this phase angle. And so we got a basic pulse tube we got a OPTC, we got DIPTC, and now I am going to talk more about inertance tube or pulse tube cryocooler which I not talked during the last lecture. And I had told that, I will talk about the inertance tube - pulse tube cryocooler in a separate lecture. The phasor diagram for basic Orifice and double inlet PTC also we had seen.

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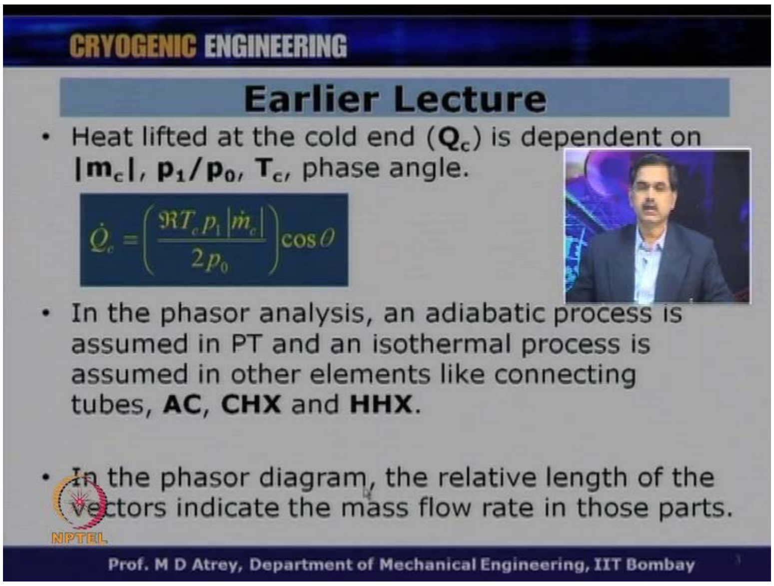

We had seen that the heat lifted at the cold end that the cooling effect depends on the mass flow rate at the cold end. The P 1 by P o ratio that is amplitude of P 1, and that is actually indirectly reflect the pressure ratio generated in a system, the cold end temperature T c at which cooling effect is obtained, and phase angle. And all these are connected by this formula. So, Q dot c is equal to RTC - P 1 by P 0 m dot c into Cos theta divided by 2. And we had see in the phasor diagram - And in the phasor diagram, in the phasor Analysis, an adiabatic process is assume in the pulse tube. And an Isothermal process is assumed in other elements like connecting tube, after cooler, cold end heat exchanger and hot end heat exchanger. Depending on this assumptions, we had ultimately derived; these relationship between the cooling effect and various Parameters.

In the phasor diagram, the relative length of the vectors indicate the mass flow rate in those parts. We had seen the mass flow rate for the entire pulse tube cryocooler, and I will just show that again in order that you understand what we had done in the last lecture.

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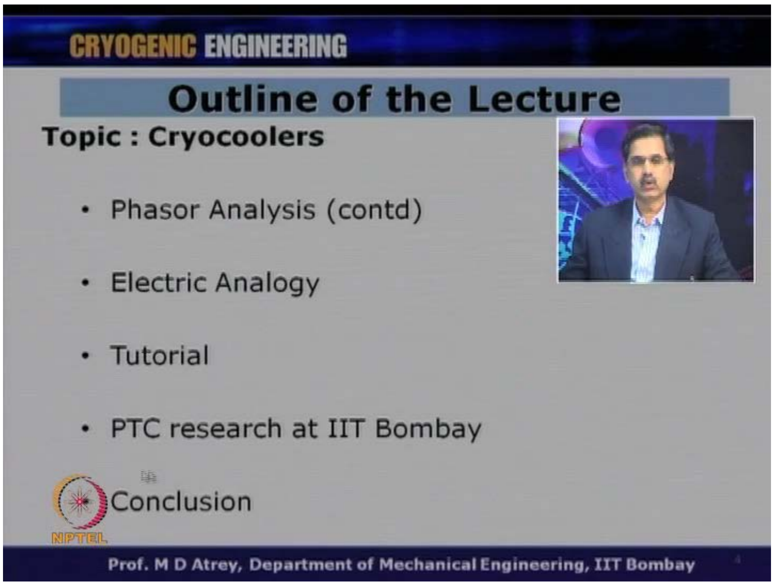

So, in this lecture now, taking ahead from what where we left during the last lecture. I would like to continue with the phasor Analysis, and I would like to give a electrical analogy to understand what is this inertance tube business basically. So, normally we understand RLC's, the resistance, the inductance, and the capacitance circuit. And we know the relationship between the voltage, and the current. And therefore, I would like to (( )) explore the fact regarding RLC circuit in order to understand the the phasor diagram.

I will take a small Tutorial based on this phasor diagrams. So, that you understand the concepts or related to calculations of the pulse tube cryocooler. And then, I will spend the second half of this lecture on the pulse tube cryocooler research at IIT Bombay. And I would like to show various parts which we have developed at IIT Bombay, various pulse tube cryocooler which we are developed at IIT Bombay. And the results related to those pulse tube cryocoolers. Finally, I will conclude the entire chapter on the cryocoolers, because this is the last lecture on the cryocoolers.

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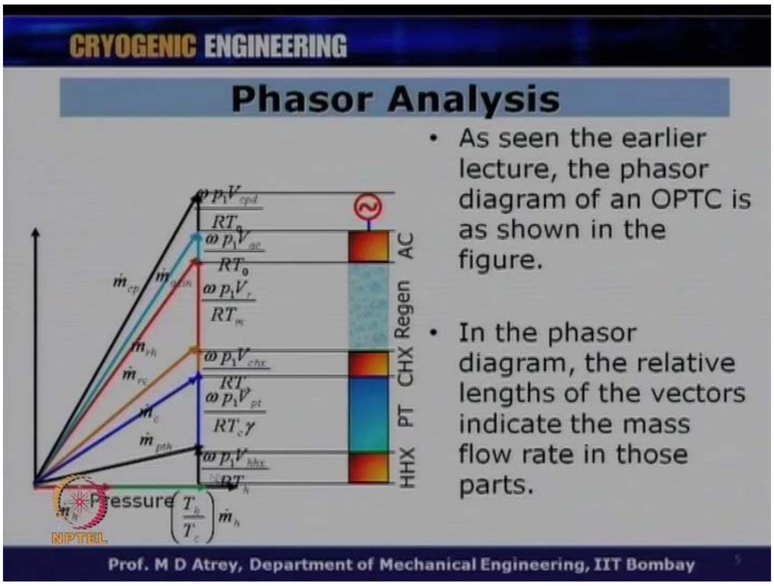

So, let us see phasor diagram. As seen in the earlier lecture. The phasor diagram of an OPTC is as shown in the figure. And this was our m dot h and on this the pressure axis we got a m dot h which is in phase for an OPTC, because it is a Orifice only; and on which T h by T c into m dot h, this is this vector. Then we have got a length associated with heat exchanger - hot end heat exchanger (( )), this is the hot end to the pulse tube.

So, we have got a omega 1, omega P 1, VHX divided by P m into T h which is the volume of the hot end heat exchanger divided by corresponding temperature T h, and then I get mass flow rate at the inlet of the heat exchanger. It is let us say, pulse tube hot end. And they got a, I have got pulse tube; corresponded to pulse tube accord the V PT upon T c. And what I have got here m PT h, and what I got here m m dot c. This is the mass flow rate at cold end. And this is which is very important, because it generates cooling effect.

Then at the other end of cold end heat exchanger, what I have is the regenerator at the cold end. So, depending on the volume of the cold end heat exchanger divided by its temperature, I got m dot RC which is the mass flow rate of the regenerator at the colder side. And then, I have got a regenerator. So, depending on what is the volume of regenerator divided by its temperature there, I will get now m dot R a - that is mass flow rate at the hot end of the regenerator. So, understand the fact that, I am basically adding each volume divided by its temperature to give the mass flow rate in that part alright.

So, depending on the volume of that particular part divided by its temperature, and depending on where there is a adiabatic process or a Isothermal process. For example, PT is a adiabatic process, we got a gamma over here, while where assume that this process are basically the isothermal. And therefore, there is no gamma below in the denominator for this mass flow rates.

Then we got a after cooler, and associated with the volume of the after cooler, we have got the vector again which is basically coming from now compressor. And then, we got a dead volume associated with the compressor. So, I I got a V cpd, and this is the dead volume associated with the compressor, and the connecting to be (( )), this is m dot CP. This is the mass flow rate from the compressor to be delivered to the entire cryocooler. Now, understand that, and beyond this we can have (( )) volume of compressor if one (( )) two.

So, I need to compress, so much of gas to get m dot c at the cold end the pulse tube to generate cooling effect. And this my net theta - the theta being angle between mass flow rate at the cold end, and the pressure vector. So, in order to get this theta between m dot c, and pressure; I have to compress so much of gas at the compressor. The compressor power will definitely increase, depending on the dead volume for the system - if my dead volume is more here, my compressor volume will be still more and more. And therefore, I this vector of m dot CP, the length is going to be much higher as compare to m dot c.

So, actually in directly talks about the COP of the system. How much gas has to be compressed; that means, how much power input has to be there. And how much cooling effect do I get basically, when I compress so much of gas. So, cooling effect divided by power will give me the COP and therefore, the phasor diagram is a simple indication - it is just an indication. We have have taken various assumption of you know having isothermal processes and adiabatic processes, but if an indication into also shows you the relationship between m dot c, and the pressure. But it also talks about how much power input goes, in order to get the corresponding cooling effect.

So, in the phasor diagram, the relative lengths of the vector; you can see the relative lengths of the vector in a vertical direction, as well as in the inclined directions. They give basically, they indicate the mass flow rate in those parts. So, this is mass flow rate in the pulse tube; this vector gives a mass flow rate at the outlet of the cold end heat exchange which is m dot c. Then mass flow rate at the outlet of the regenerator which is m dot RC, then mass flow rate at the inlet to the regenerator which is m dot R h and thing like that. So, it is a very important diagram, and we have done the entire derivation during the last lecture

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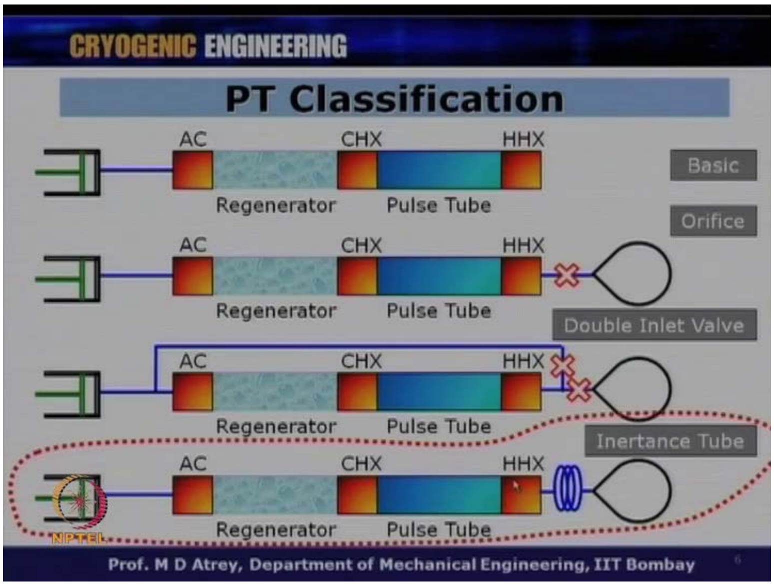

Going ahead from there, coming back to the pulse tube classification which I had shown you earlier, we got a basic pulse tube, we got a Orifice Pulse Tube, we got a double inlet pulse tube. And what we also have is inertance tube pulse tube and about which we had not talk during the last lecture; and it said that I will talk about inertance tube in a separate lecture. So, this is a, this is something I would like to talk about and to understand this concept, I would like to have a electrical analogy. So, that you understand how do you compare, how do you see a performance of inertance tube as compare to; for example, the orifice pulse tube.

Normally we do all comparison with respect to OPTC. So, let us seen OPTC, and let us in the relationship to that; let us see ITPTC that is inertance tube pulse tube Cryocooler.

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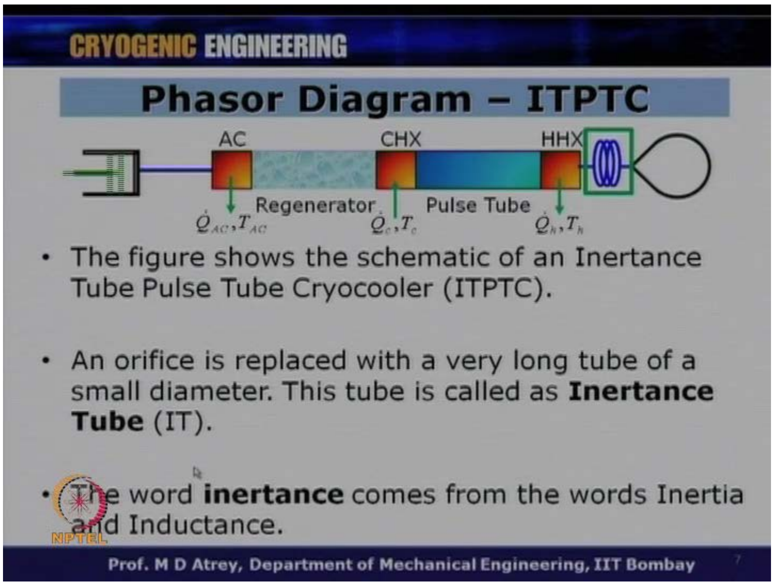

So, this is my inertance tube pulse tube cryocooler. We got a (( )) after cooler, regenerator, cold end heat exchanger, pulse tube hot end heat exchanger, and this hot end heat exchanger in a OPTC will be connected through an or (( )) to a reservoir. Now, I am getting read of orifice, and I will have a inertance tube which is a small diameter kind of a capillary tube running into length, of let us say 1 meter to 2 meter depending on the diameter, and it get in connected to a reservoir.

So, the figure shows the schematic of an inertance tube pulse tube cryocooler ITPTC, an orifice here, for a OPTC gets replaced by very long tube of a small diameter, and this to be as called as inertance tube or IT in short.

The word inertance comes from the word inertia and inductance. So, we know the electrical circuit - In electoral circuit, we have got a resistance, then inductance and capacitance. So, in fluid flow now, we have got a inductance replace by a term called inertance which basically talks about inertia; inertia nothing but the mass - mass flow rates. So, in fluid mechanics I will have inertia replace by mass flow rate, and inductance. And if you combined these two, what you get is a basically the term called Inertance.

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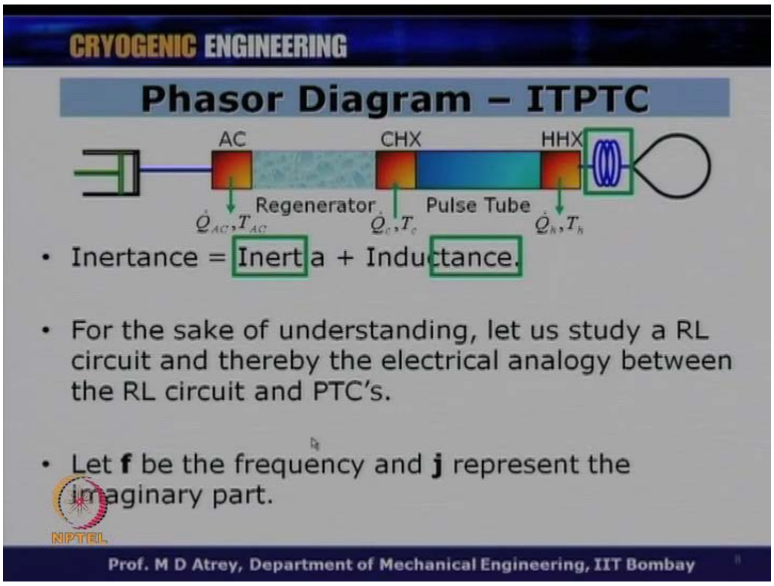

So, inertance is nothing but inertia plus inductance, which shows at mass flow rate through a inductive circuit or through a tube, which is running in length; it has got a diameter, it offers impedance to the flow rate. It (( )) inert inductive impedance to the flow rate, and that is why we call at inert from here, and trance from here. And this a word called inertance has been generated in fluid mechanics. For the sake of understanding, let us study now RLC circuit, and thereby the electrical analogy between RLC circuit, and PTC.

I would like to deviate from here, (( )) some glances of basics of resistive, inductive and capacitive circuits. And I will come back to the pulse tube cryocooler. So, that we understand the inertance tube business in detail.

Let f be the frequency, and j represent the imaginary part. You know the real part and imaginary part, any vector can be replaced can be return in a real plus imaginary part, and that is what I would like to use in this case.

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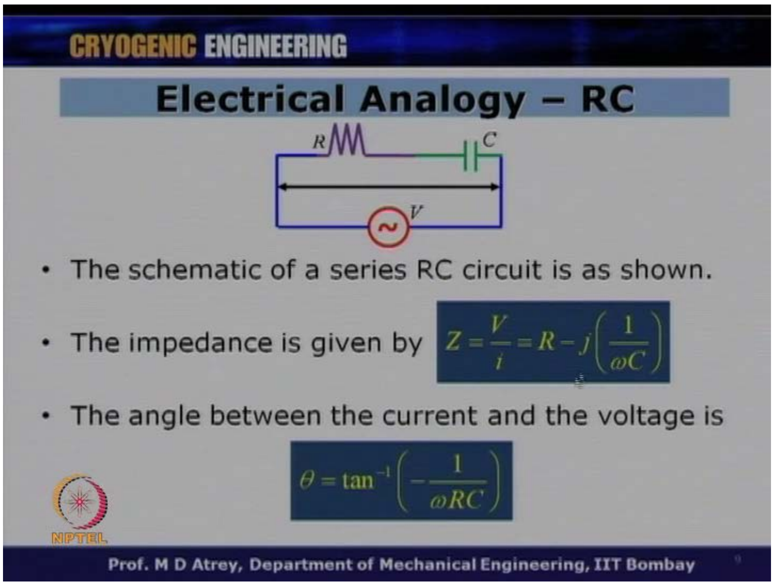

So, let us see a simple RC circuit which is resistive plus capacitance circuit, and you got a voltage across is and therefore, a current will flow through it alright. And this current will have impedance in the form of resistance plus capacitance. There is no inductance in this case, and the voltage across the resistance, and C capacitance is called V. So, schematic of a series RC circuit is as shown here. The impedance is given by Z; and this Z is called as V upon I, in a pure resistance circuit this Z will be equal to R alright. But in a inductive circuit this Z is equal to R minus j into 1 by omega C. I will not going to the very basics, but most of you know this definition how the impedance of a RC circuit, RLC circuit, and RLC circuit is written as.

So, this Z is equal to V upon I which is equal to R minus j into 1 by omega C alright. This is the vector L, addition basically the angle between the current and the voltage will be given by tan theta, which is nothing but tan inverse of one upon omega C divided by R, that is one upon omega RC. And you can see a negative sign over here; that means, this theta is going to be negative in this case alright. So, in that case my Z, because Z being negative now; if I add a vector ally this thing, Z will always been the 4 th quadrate. If I plot this Z my depending R, because R is going to be positive and this term is going to be negative. So, if I want to have vectorial addition R minus j upon omega C, I will have R S positive direction towards x axis, and then minus one above omega C which is coming to 4 th quadrant. And therefore, Z will come in the 4 th quadrant as is obvious from here, because tan theta is negative.

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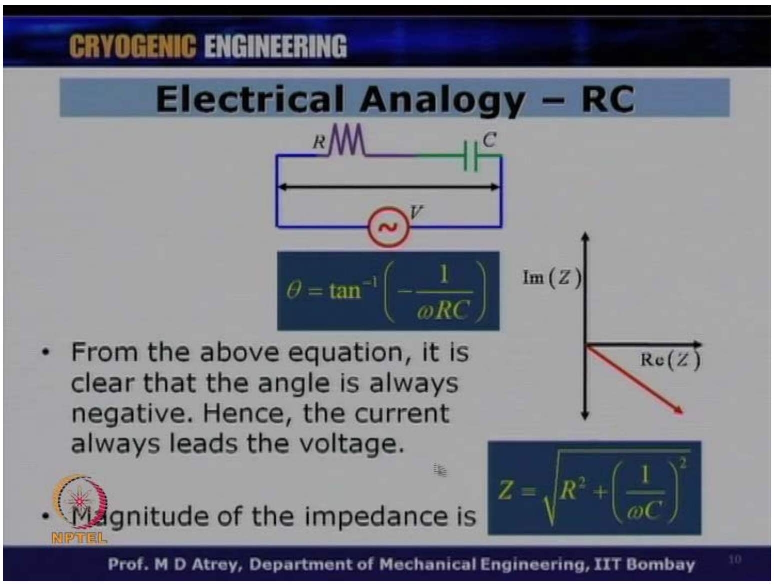

So, theta being negative in this case, this is my plotting of Z; in this case you got a real part, on y axis you got imaginary part. So, Z therefore, will have R minus one upon omega C, j time minus j one upon omega C. And therefore, Z will always be in the 4 th quadrant as shown here. From the above equation, it is clear that the angle is always negative. Now, in such a situation - in such a situation my current will always lead the voltage. So, you know that in a RC circuit, in a resistive circuit current and voltage are in phase.

In a RC circuit, the current will always lead the phase; that means, current will be ahead. So, let us say this is current, and this is going to be voltage in that case alright. The direction this is actually a Z vector basically, but in this case, if I take this as I - this I will lead the voltage vector. And therefore, current will always lead the voltage. This is basically to understand from a RC circuit. And magnitude of the impedance is under root of R square plus 1 upon omega C whole square, this is standard basically for any imaginary any any a plus I b vector

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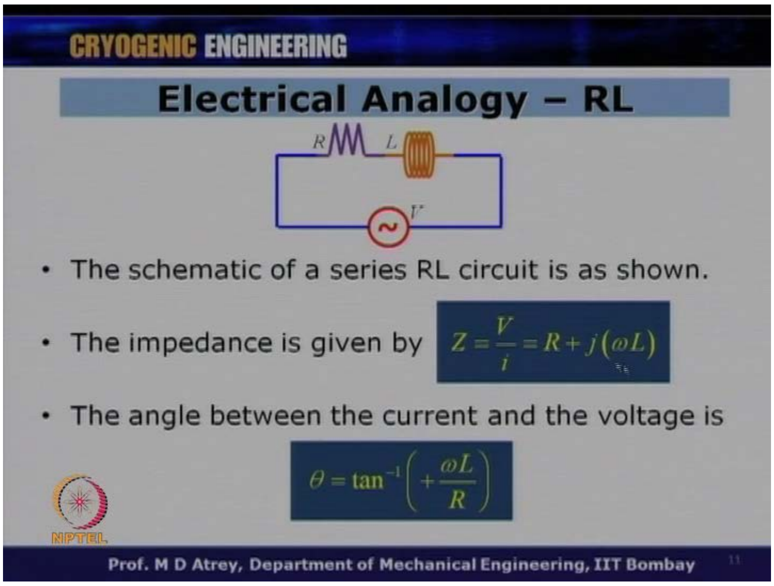

Now, let us go to RL Circuit. The schematic of a RLC circuit is shown over here, the impedance is given by V upon I R plus j omega L, if you see earlier equation we have got now R plus j omega l; that means, this is positive and this is also positive. In this case now, voltage will lead the current; that means, current will lack alright; if you add, because R is going to be positive towards x direction, while omega L is going to be at a angle over there and therefore, V will now lead the current in this case. The angle between the current and the voltage, therefore will be a positive angle tan inverse of omega L upon r; so, this is my theta.

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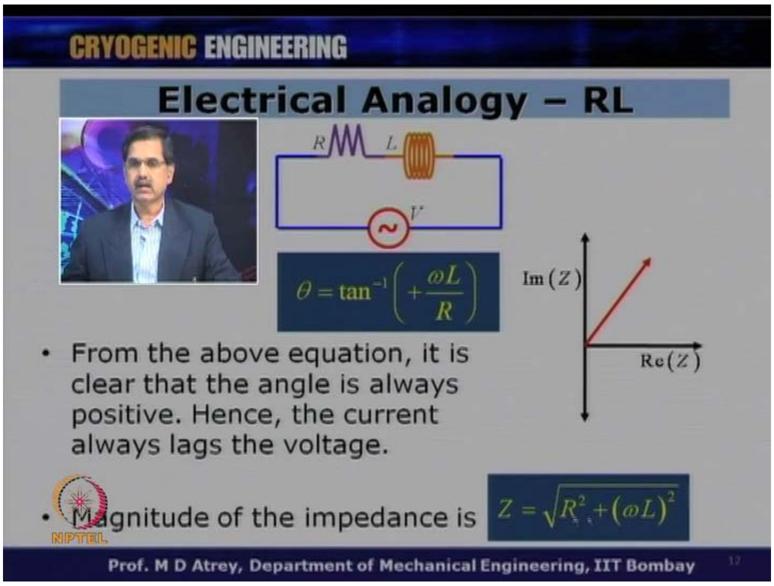

And in this case now, Z will be in the first quadrant. Earlier case Z was in the 4 th quadrant. So, in a in a resistive plus inductive circuit now, the theta is going to be positive; and because the theta is positive. From the above equation, it is clear that angle is always positive and therefore, in this case current always lags the voltage or voltage leads the current. In earlier case, current was leading the voltage. In this case, current always lag the voltage. So, RLC circuit current always lack the Voltage. And magnitude the impedance is R square under root of R square plus omega L square

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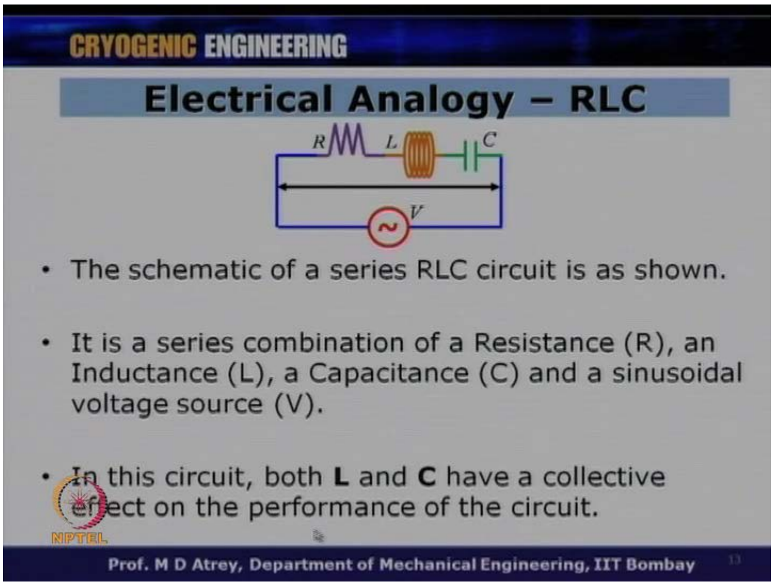

Now, let us come to the RLC circuit, where resistance, inductance and capacitance are in series basically. So, schematic is shown over here, it is a series combination of RL and C and a sinusoidal voltage V; in this circuit both L and C have a collective effect on the performance of the circuit as you know this thing.

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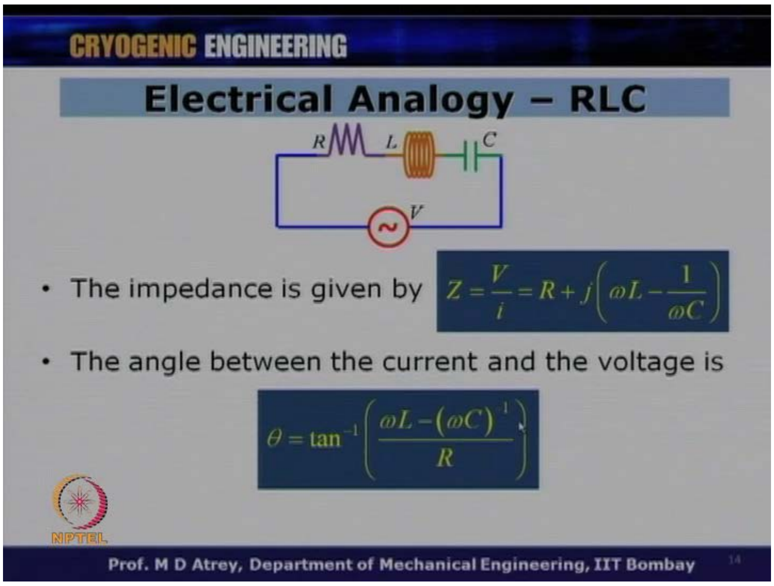

And the impedance will be given by or Z will be given by R plus j time omega L minus one upon omega C alright. And now theta will be given by tan inverse of this component divided by R, that is omega L minus omega C inverse one upon omega C divided by R. Now, the value of theta will depend on what is the net result of this - what is my omega? What is my L - and what is my C.

So, omega L minus omega C will determine, where theta is going to be positive or theta is going to be negative. And this is very important to understand alright; this is a very simple state mathematics, this please understand that theta is going to be determined by this numerator, because R is always positive.

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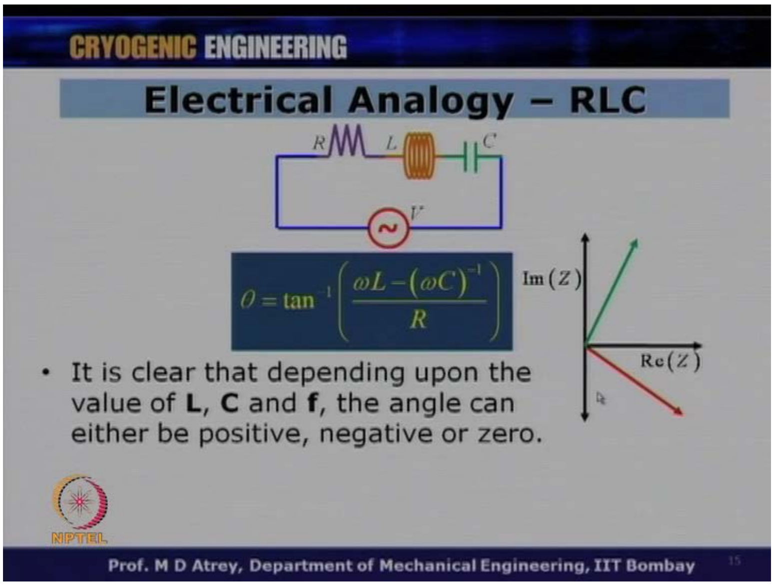

So, theta is going to be tan inverse of omega L minus omega C inverse divided by R; and depending on the value of this, I can have a theta from positive to negative; that means, I can have Z vector in the first quadrant, and also in the 4 th quadrant; I have got all the possibilities depending on the value of the inductance, the omega and the capacitors.

So, it is clear, the depending upon the value of L C and f; f is basically give in the omega 2 phi f is nothing but equal to omega, the angle can either be positive and negative or 0. So, it can have any variation possible from being in the first quadrant, being on the Z axis being being on the x axis as well as being on the 4 th axis. So, all the variations are possible positive 0 or negative; depending on the value of omega L and omega C. And therefore, in a RLC circuit now, I got lot leverage to play with the Z vector and this is what I want to come back to basically alright.

So, in addition to L and C, frquency plays a very important role. Now, if a frquency is very high, then only this circuit become very important; and this becomes a frequency dominant circuit. If omega is very small the inductance will not play any role in that case, it becomes purely RC circuit, but omega is being high; the inductance comes you to picture and therefore, inductive circuits are very very important with during high frquency , for high frquency operation

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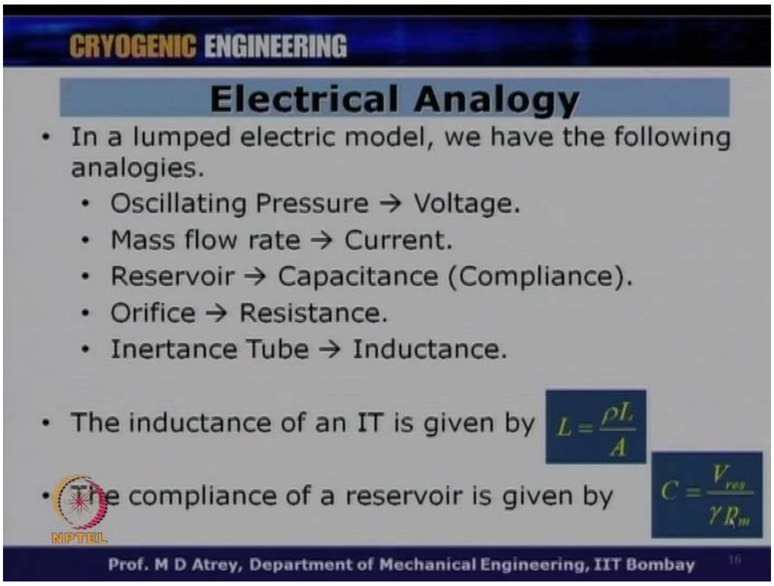

Now, coming from electrical analogy to pulse tube cryocooler; now, I got comparative Parameters to the RLC circuit in the fluid mechanics; and fluid mechanics I am talking about the pulse tube cryocooler fort example, Oscillating pressure will give me the Voltage. Alright when I have got a delta P across, when I have got a pressure of variations current passes. So, because of the voltage current passes between, because of the delta P, because of the pressure variation mass flow rate is there. So, mass flow rate is nothing but analogous to the current, because of voltage current is there, because of pressure variations mass flow rate is there. So, this is I, this is v.

Then we (( )) reservoir alright; we got a capacitance therefore, which is called as compliance sometimes in fluid mechanics. Therefore, we got a Voltage, current, capacitance; we got a orifice, as you know Orifice flow flow through Orifice will be always be proportional to delta P across it. And therefore, a pure Orifice normally is called as a resistance to the flow alright. So, this is always going to be kind of a resistance in the circuit.

An inertance to be nothing but inductance; which is having mass flow rates. So, we have got a inertia plus inductance. So, inertance tube basically nothing but a tube, which offering inductive impedance through which the mass flow rate flows. So, the mass flows alright. So, we got a inertance tube also here. And the inductance of an inertance tube will be given by rho into L by a rho is a density of the fluid L by a, the Reservoir compliance is given by V, volume of the Reservoir divided by gamma which gas divided by P m again these are standard Parameters.

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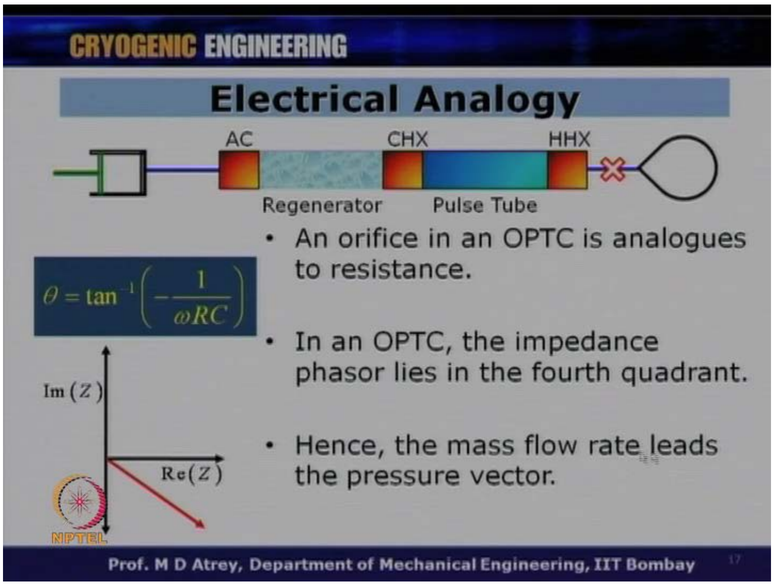

Now, let us have a Orifice; let us see this electrical analogy to OPTC and ITPTC. So, an Orifice in an OPTC analogous to resistance; so, we got a theta is equal to tan inverse of minus omega RC, this is what we had seen; and here now we know that the current the impedance lies in the 4 th quadrant, we had seen these and in this case now we know that mass flow rate leads the pressure vector.

So, if you remember the phasor diagram, we had m dot c is leading the pressure vector; m dot c was having an angle of theta to the pressure vector, and this is what is getting proved in case of with I LC circuit in OPTC, I have got only resistive and capacitance; I got orifice and the reservoir, this is the resistance and this is the capacitance. And in this case, my impedance vector is going be in 4 th quadrant, and my mass flow rate which is m dot c leads the pressure vector, this is what we had seen earlier.

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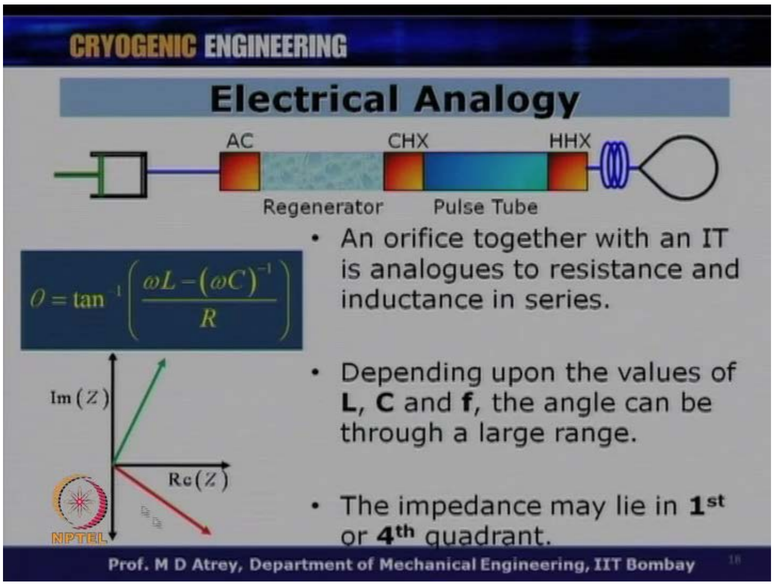

And for a inertance tube now, I want to prove that an orifice together with the inertance tube now is analogous to resistance and inductance. It has got small opening. So, we got a inductance, capacitance alright; so, we got a RLC circuit over here, now and in this case my tan theta will be omega L minus omega C inverse divided by R; depending upon the value of LC and f the angle can be changing through a large value now.

My angle now, will have we have seen earlier. My impedance vector can be positive in the first quadrant or in negative in the 4 th quadrant. So, now I can have a large variation that is possible of theta for a RLC circuit; and therefore, when you have inertance Tube, you have to work with high frquency, because inertance is always omega into L, and now in this case depending on the diameter of this tube, and the length of the tube I can have theta whatever I want to.

So, my impedance now could be in the first quadrant or in the 4 th quadrant; and I can play with the theta angle. So, here in a inertance tube PTR, PTC; I have got a large possibility of changing my theta and therefore, always for a high frquency PTC, I will have a inertance tube associated with theta. I will not have only Orifice or a I will not have double inlet PTR, but I will have inertance Tube, and may be I can add double inlet to it also, but what is most important for high frquency is the inertance tube and, because of now diameter and the length of the inertance Tube, I can have theta whatever I want alright. So, this is the most important thing related to ITPTC

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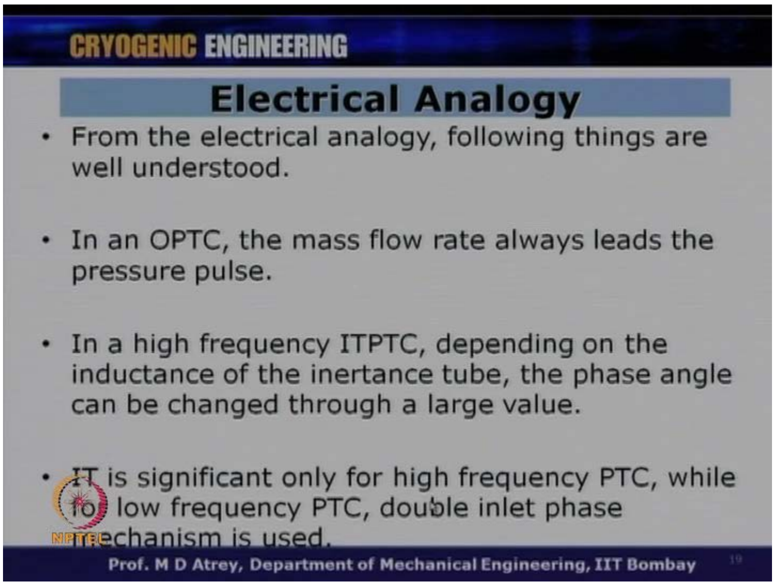

So, what I have understood, what we have understood from here, I will just want to show you that from the electrical energy following things, have been while understood in an OPTC the mass flow rate always leads the pressure pulse; this is what we had say. So, always a theta angles - theta angles remains in OPTC, because it is a resistive pulse capacitance circuit. While in a higher frquency ITPTC depending on the inductance of the inertance Tube; the phase angle can be changed through a large value. And therefore, ITPTC I am able to make minimize this theta, by optimizing the IT inertance tube length and a diameter.

So, now I have got a very big possibility to change the inertance Tube, inertance inductance of the circuit. So, that my theta gets minimize, because now my Z vector can lie in the first quadrant or in the 4 th quadrant, but I have to see that correct diameter and lengths have been properly chosen. This is the most important thing and therefore, ITPTC I can now make my theta very very close to 0 or even negative if I want to. So, inertance tube is significant only for higher frquency pulse tube cryo cryocooler, I have just said that, because its omega into l.

While for low frquency PTC normally, double inlet phase mechanism is used not the inertance tube will not be used for low frquency machine, that is the GM type pulse tube cooler. For GM type pulse tube cooler, you will hardly find inertance to be used, but for Stirling type pulse tube cooler, where inertance to machine works at a very high frquency will always use inertance tube for that. And this is what I wanted to tell you, choosing electrical analogy for the ITPTC; I hope you understood, this please understand your basics principles of RLC circuit, and try to a compare or find an analogy with the ITPTC, OPTC etcetera using what I have told you in this slides.

Going ahead from here, I will just like to take a small Tutorial. So, that you understand the phase diagram. So, the Tutorial is basically aiming at development of a small phasor diagram. So, that you will understand the principle of phasor diagram.

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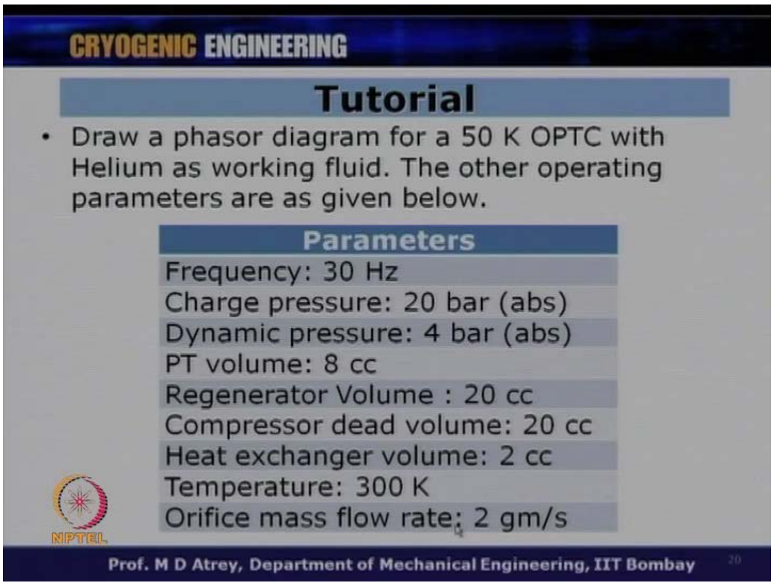

So, Draw a phasor diagram for a 50 K OPTC with helium as working fluid; the other operating Parameters are as given below. So, I have got a Frequency of 30 hertz, Charge pressure is 20 bar, Dynamic pressure as 4 bar pulse tube volume is 8 CC, the regenerator volume is 20 CC, the compressor dead volume is 20 CC which is very high. I can have even compressor step volume added to it, but I have not added this; heat exchanger volume is 2 CC, temperature is 300 kelvin on the ambient side while the Orifice the mass flow rate through Orifice that is m dot o is given as 2 gram per second. The (( )) is now Draw a phasor diagram for this OPTC, this is the Orifice pulse tube Cryocooler.

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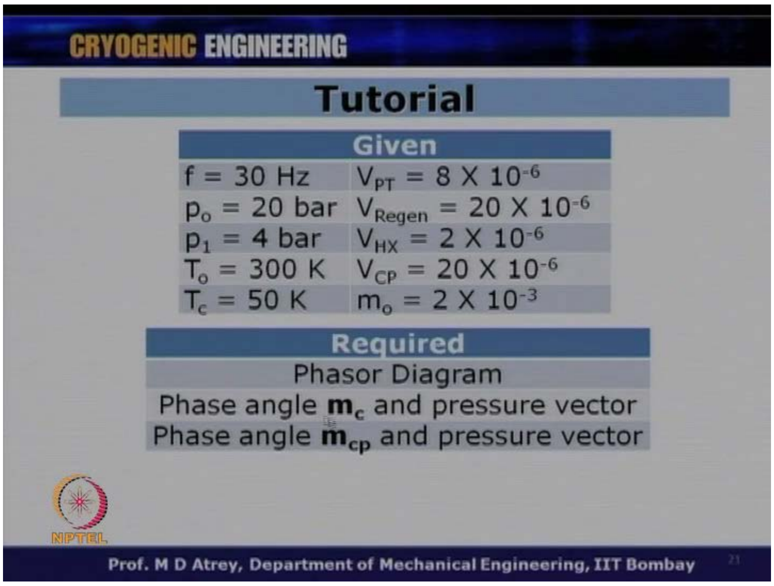

So, these are the parameters which is given VPT, V regen , VHX, VCP dead volume m dot o, then f 30 hertze P o as 20 bar, P 1 as 4 bar, T o as 300 kelvin and T c as 50 kelvin. What we want to find out is phasor diagram; that is phase angle m dot c between the m dot c and the pressure vector; and also phase angle between the mass flow rate at the compressor and the pressure vector.

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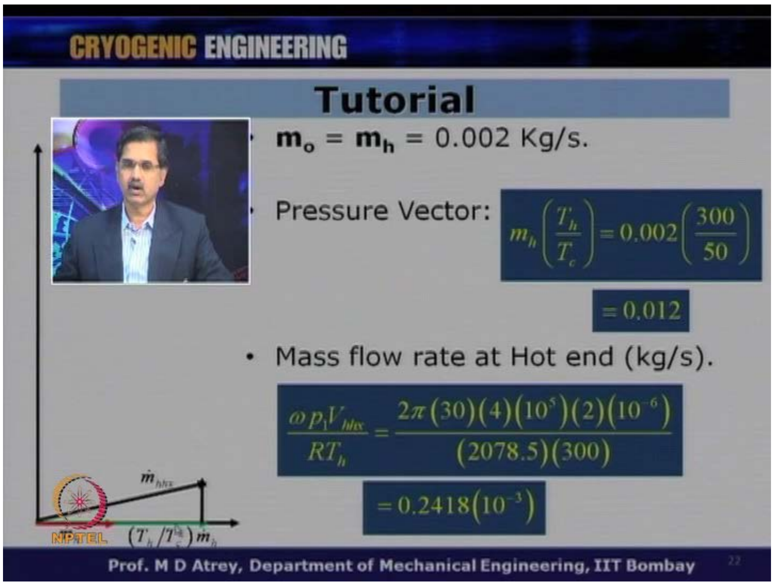

So, begin with I know m dot o is equal to m dot h for OPTC which is given as 2 gram per second, which is 0. 002 K g per second. Then, we know the pressure vector is going to be horizontal, and on the pressure vector we have got a m dot h (( )) plotted, and then what we have is a m dot h into T h by T c alright. So, I will have now T h by T c into m dot h which is 0.002 into 300 by 50, because my cold end temperature is 50; and this gives a 0. 012 so on. These now, I will build buildup a vector which has got a length of 0.012. This you can take any scale to begin with and Draw all these diagrams.

Now, depending on the volumes of hot end heat exchanger pulse tube regenerator, I am going to find the mass flow rate through these different parts. We have already given the equations to this. So for example, I want to find out mass flow rate to the hot end heat heat exchanger exchanger where I will use therefore, omega into P 1, V HX which is volume of the hot end heat exchanger divided by T h and divided by r.

So, omega is 2 phi f, P 1 I have given as 4 bar convert it to the appropriate unit, V HX as given as 2 CC convert it to appropriate unit of meter cube, R into T h. So, having done this, I get this value this is K g per second, and I will add this vector at 90 degree to earlier vector, I will get now mass flow rate at the inlet to the heat exchanger. This is mass flow rate out of the heat hot end heat exchanger or so Orifice, and this is my mass flow rate to the inlet to the hot end heat exchanger.

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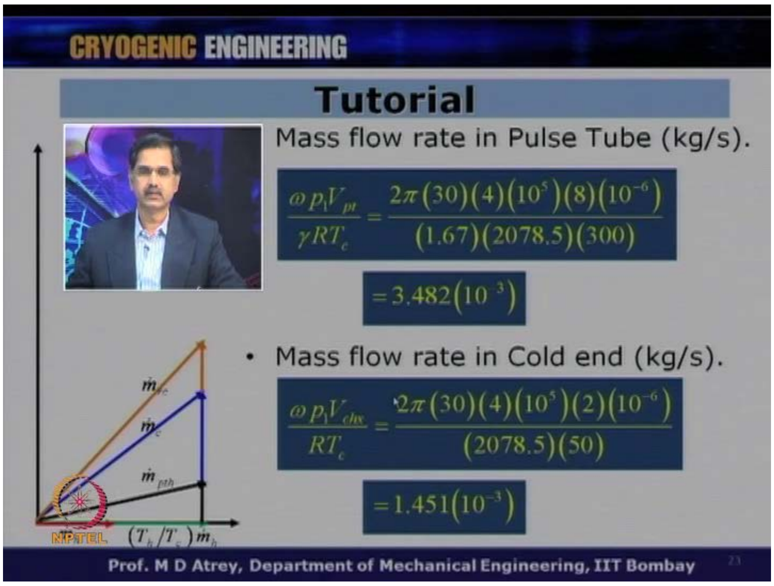

So, depending on these now, I will have a mass flow rate to the pulse tube; like this and now I will add on this vector. So, now, at the cold end on the pulse tube, I will have m dot c. This is the volume through the pulse tube divided by heat temperature as given by mass flow rate in the pulse tube. Then mass flow rate at the cold end heat exchanger, depending on the volume of the cold end heat exchanger depending on the volume of the cold end heat exchanger and temperature there, I will have vectors.

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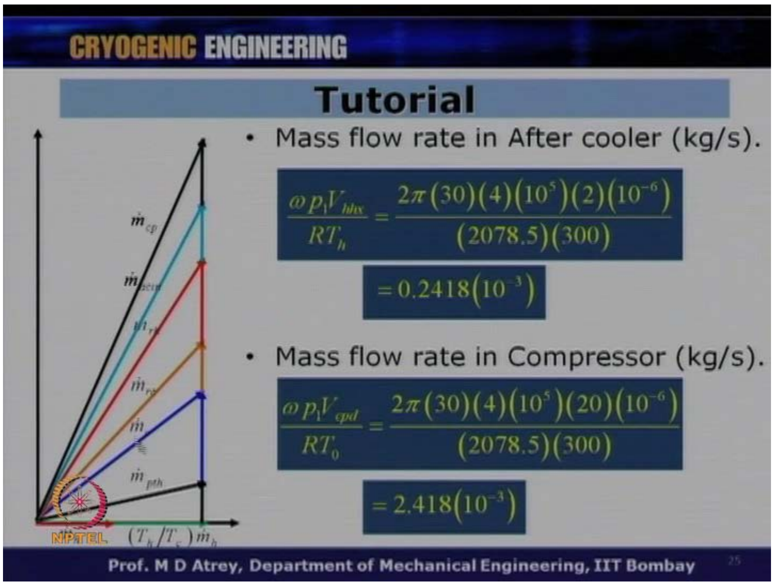

So, I will complete this diagram. And I will not go into this type. So, I want to have respect to temperatures in the denominator. So, I will normally will take logarithmic mean temperature for regenerator. So, this is my temperature of logarithmic mean, and I will have a vector which gives me the mass flow rate through the regenerator as 5.2 gram per second or 5.2 into 10 to the power minus 3 K g per second and I will Draw according to length, I have got m dot R h. This is mass flow rate, at the regenerator entrance for the hot end basically alight.

And then, I got a after cooler, and now I will mass flow rate at the compressor outlet which is depending on the whatever dead Volume, I have I have got a clearance volume of compressor, I have got connecting to (( )) compressor and correspondingly I will get now. So, I should get mass flow rate corresponding to this length, to be compressed in the compressor; it should leave the compressor which has got this much flow rate in order to get m dot c equal to this.

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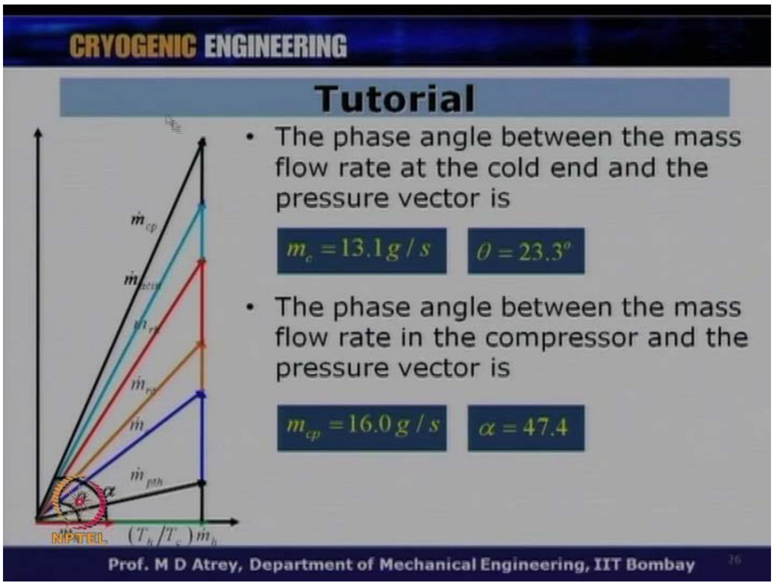

This is what, we learn from this. And what is the phase angle, this is the phase angle theta - the phase angle between the mass flow rate at the cold end, and the pressure vector is the m dot c is 13.1 gram per second and theta is 23.3 degrees. The phase angle between mass flow rate at the compressor; in the compressor and the pressure vector is this is 16 gram per second here to be compressed, and correspondingly I have got alpha is equal to 47.5. So, alpha is equal to 47.4, while theta is equal to 23.3 which is a good job done by this OPTC of given diameters.

So, this is my phasor diagram, it shows me that the compressor flow at the outlet should be of this length, corresponded to this length approximately in order to get m dot c, at an angle of theta of this length alright. So, this is where I understand that, if I dead volumes are more and more my compressor gas to be compress good be very very high. So, understand that, this dead volumes in the regenerator the the heat exchanger play very important role; and therefore, depending on dead volumes I will have to compress more and more gas in the compressor; which means my power input the compressor will go on increasing accordingly, this is a very important thing.

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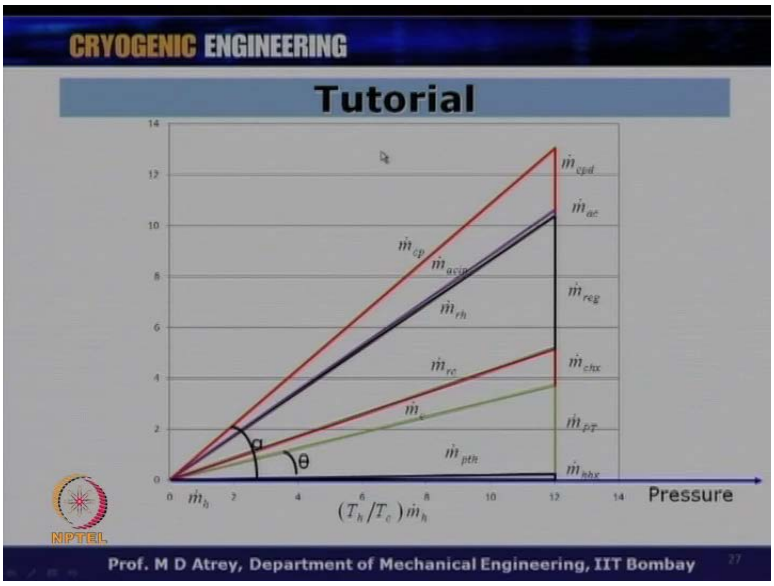

So, this is my final diagram. I will drawn on excel sheet. What it it will look like to show you exactly on the pressure axis, you got a m dot, c m dot HX; and this is Drawn to the scales. So, you can see now how does this diagram look. Basically, it is same thing as what we have drawn, but this is with correct dimensions given over here. So, with this background on the pulse tube cryocooler; I will now you show you, the pulse tube research at IIT Bombay.

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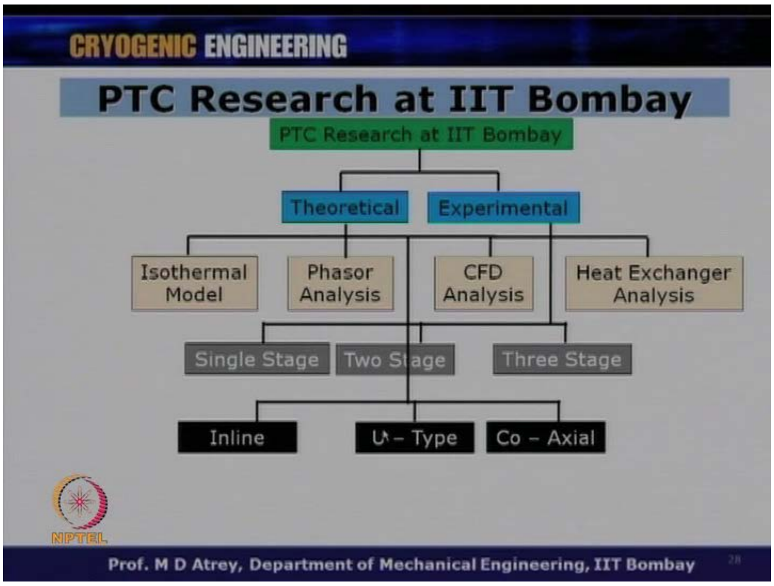

So, let us see what we have done and so, you can see what kind of research has been happening at IIT Bombay; and you can see I would like to show you different develop parts pulse tube cryocooler at IIT Bombay.

So, let us see the pulse tube research at IIT Bombay is in 2 parts - one is the theoretical research as well as the experimental results. So, you got both the works going on theoretical front, as well on the experimental front; if you as a theoretical work is normally, the modeling and simulation kind of thing where we have developed isothermal model, then we have got a phasor Analysis, we have working on CFD analysis of pulse tube cryocooler as well as, as you know lot of heat exchangers involve the regenerator, the hot end heat exchanger, the cold end heat exchanger etcetera. So, we have doing lot of work on the heat exchanger analysis also as far as, theory of the pulse tube cryocooler is considered.

Now, under the experimental work, we have developed various cryocoolers, taking various projects from different agencies, the funding has to come for Experimental work and we have developed various single stage pulse tube cryocooler, we had developed two stage cryocoolers, as well as we are developing, we are in process of development of the three Stage pulse tube cryocooler also.

And in both cases, both for theory and experiments we want to understand or we areunderstanding different geometries of the pulse tube cryocooler, which are basically inline U type, and Co axial; I have talked about these during earlier presentations. So, inline is the one with the regenerator, and the pulse tubes are inline. In the U type, the regenerator and the pulse tube are in this U direction or parallel to each other, and coaxial the regenerator and the pulse tube are actually, the regenerator outside and the pulse tube is inside. So, the regenerator kind of angular to the pulse tube.

So, let us see all this parts, I would like to show the regenerator mesh material what we use and thing like that ;try to understand I may be going very fast, to show in the limited time, but please you can see those parts fabricated also.

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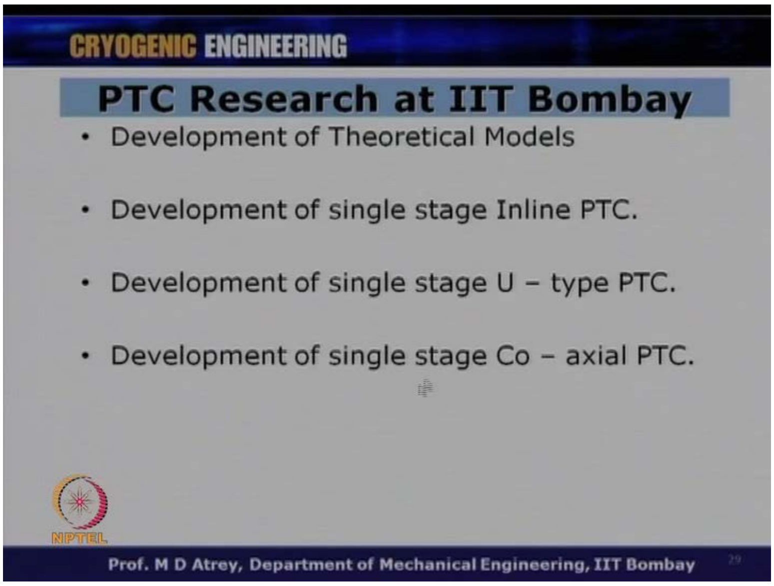

So, the pulse tube research at IIT Bombay is development of theoretical Models, development of single stage inline pulse tube cryocooler, single stage U type pulse tube cryocooler and single stage coaxial pulse tube. And this is I am getting my lecture limited to only single stage units, because I do not have much of time to show even 2 Stage units right now.

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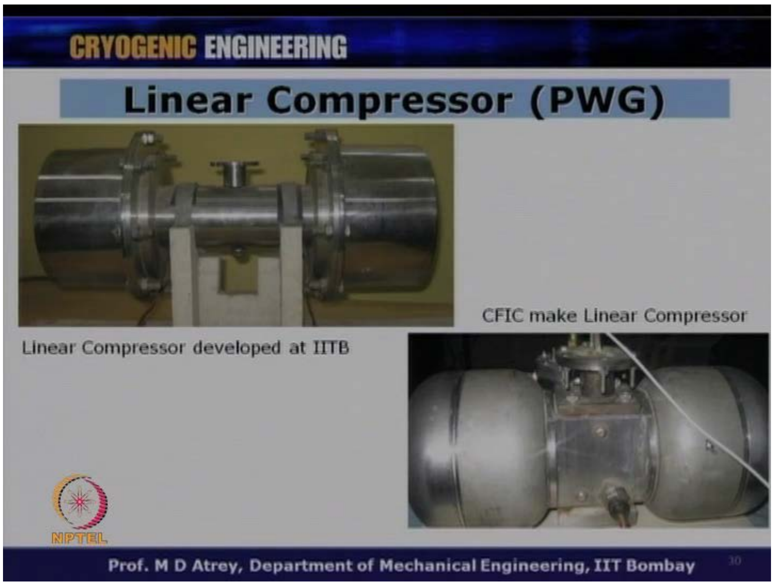

The compressor I use or a pressure we have generator, which I use is a linear compressor. The linear compressor work on the principle of linear motor; and this is the compressor which is developed at IIT Bombay, based on a post piston linear motors, you can see there are 2 pistons driven a post side, and from here the pressurized gas comes out in the form of pulse at this point. So, you got a one linear motor here, we got a one linear motor over here, and both pistons are moving towards each other which what we call as a post piston compressor developed at IIT Bombay.

And similarly, I have got one imported peace from CFIC; this is the clever fellow incorporation in USA; and because of some funding available, we have bought this compressor from outside party which is also a post piston compressor, this was a moving coil compressor, this is a moving magnet compressor, but this is also is basically based on the same principle of having linear motors at 2 ends. So, this is the pressure we have generator or this is the compressor which we use to drive the pulse tube cryocooler.

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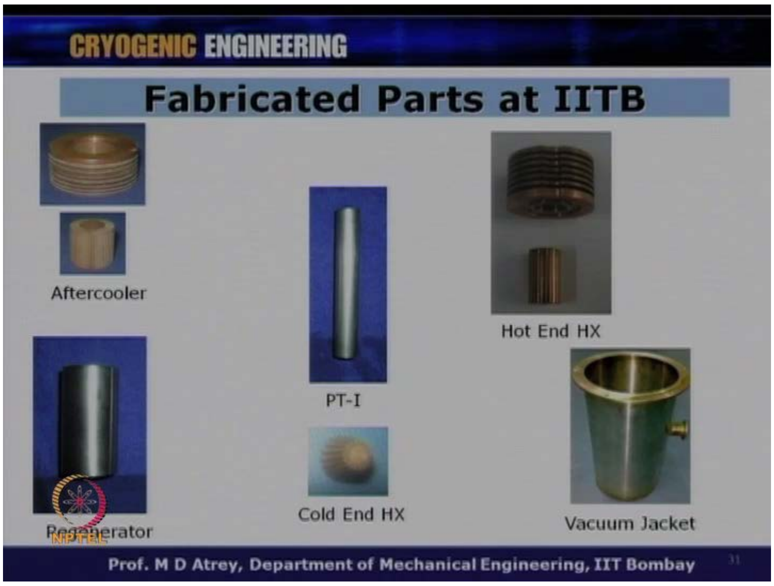

Now, I will like to show different parts of the fabricated parts, at IIT Bombay. So, this is the after cooler, and this is my fabricated part; I will just like to show you the fabricated part over here. So, you can have a look here; this is the after cooler through which water flow outside these are fines cut, and this is the inside part, and you can see the fines cut on this part. So, the compress gas comes through this fines, comes through this fines which is kept inside this. So, the compress gas will come through this fines, this is not meant for this cooler, I have taken different parts, but this will be tight fit, this will be inside fitting on this. So, the gas will come through this fines across, and this gas while traveling through fines will be cooled by the water which is flowing outside. So, I have got this circular fines on the outside through which the water will flow, and this during this flow of this gas from one end, it will enter from here; and it will go out and it during this travel, it will cool the gas, it will take the heat of compressor. So, this is basically the after cooler.

Now, let us (( )) slide again. So, second part is the regenerator, I will show a regenerator is going to be a thin wall tube, and I will show a small thin wall tube. So, here you can see a small thin wall tube, this could be any thin wall tube, but you can see this is the thin wall tube which has gotten thickness of let say 0.15 millimeter.

Why do I want such a thin tube, because I got a Hot temperature on one side, I got a cold temperature on this side; an in order that my conduction is minimize, my Q is should not get loss, I would like to have the cross section area as minimums possible. So, these are thin wall tube, thick wall tube are different; and thin wall tubes are very very important in cryogenics. Because, I will not have this thin wall s s tube, thin wall s s 3 naught 4, and the thickness as I said is 0.15 millimeter, especially fabricated for the regenerator and the pulse tube.

Next component is cold end heat exchanger: I will show a small cold end heat exchanger, which is very important again, because the gas gets cool. So, you can see this part. Again you have got fines on this side. So, the gas at the exit of the regenerator comes to these and passes through fines, and these phrases across outside. On the outside is the cold end heat exchanger. And this cold end heat exchanger is the one which transfer the cold generated in the regenerator on the Pulse Tube, to outside object to be cooled. So, this is the very important component, one can use mesh also for this. So, this is my cold end heat exchanger.

Again you got a pulse tube which is a thin wall tube, like the way I have shown it as regenerators. So, I will not going to show in the pulse tube, but as I shown earlier it is exactly again 0.15 millimeter thickness of the tube also.

This is the hot end heat exchanger which also looks like the after cooler. So, exactly in a similar way, what I will show you cool by water from outside, in the hot end heat exchanger, and the after cooler is basically the both are cooled by water from outside and you got a inside peace which is in tight fit with this, through we can always have mesh also here; through which the gas (( )), you have to have porosity through which the gas should come, and it should be good contact with this. So, outside water will cool the gas coming or flowing through this fines.

So, these are my two fabricated parts, which are which really sometimes could be wire cut or sometimes can be done by milling machine also; and this fabrication is very important. So, the water will come from one direction, and leave from other direction cooling the gas which is passing through this tube. And then, I will have a vacuum Jacket which is very important, I cannot show you vacuum jacket, because is a huge thing alright. So, vacuum jacket also is a very important entire assembly will be kept in the vacuum jacket.

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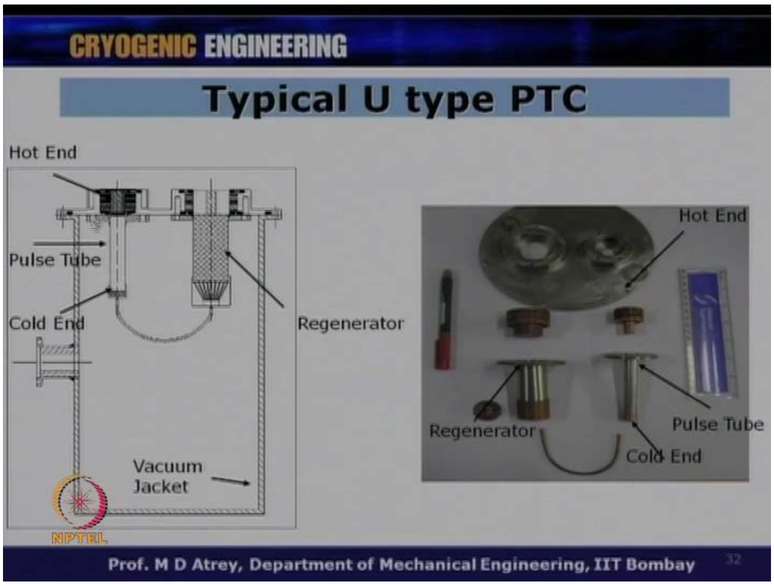

Now, I would like to show you typical U type pulse tube cooler, how will it look. So, this is my engineering drawing assembly. So, the gas comes from here, this is my after cooler, which I will just show you outside fines you can see, and inside fines part will be over here through which the gas will come, and then you will enter the regenerator. The part I have shown was cold end heat exchanger is kept at the other end of the regenerator which is like this; and then you got a U tube connecting to a pulse tube. And this pulse tube has a after cooler at this point, and entire thing is kept in a vacuum jacket, and I have shown all these part to you.

I will again show you photographer of this. So, this my top flange to which my cold, end heat exchanger is attached or a sorry the after cooler is kept over here, the gas will come from compressor, and it will enter the regenerator and this my regenerator; and at this point what I will have is a cold end heat exchanger.

And then I have got a connecting (( )) which is why it is called as U type pulse tube cryocooler, and you can see the scale also here which gives you idea of the different dimensions; this is my pulse tube, this my cold end of the pulse tube, this heat exchanger can be regenerator cold end side or at the pulse tube cold end side also. Alright, because they going to be at same temperature, because of the copper connectivity; normally the temperature at the cold end heat exchanger or the regenerator cold end and the cold end pulse tube will be same, and because the diameter of the regenerator is little higher, you have got more heat transfer area available at this point. And therefore, we put this cold end heat exchanger at the regenerator colder end.

And now, you can see the hot end of the pulse tube. And this is the heat exchanger at the hot end of the pulse tube, both of these heat exchanger are cooled by water. So, you can have water coming, and then divided into two parts. One is cooling the gas at the compressor, and one part is cooling the gas at the hot end of the pulse tube alright. So, you can see, all this fabricated parts over here; this is my top flange - this top flange sits on this vacuum jacket. So, anybody wants to work on these research, you can see this parts, and you can have you know first (( )) information about different fabricated parts at IIT Bombay. And anybody wants to work on these can always sent in email, and we can always talk about how these parts are getting fabricated, who are the fabricators, because we have developed various fabricators for for example, wire cutting, the fing cutting and thing like that.

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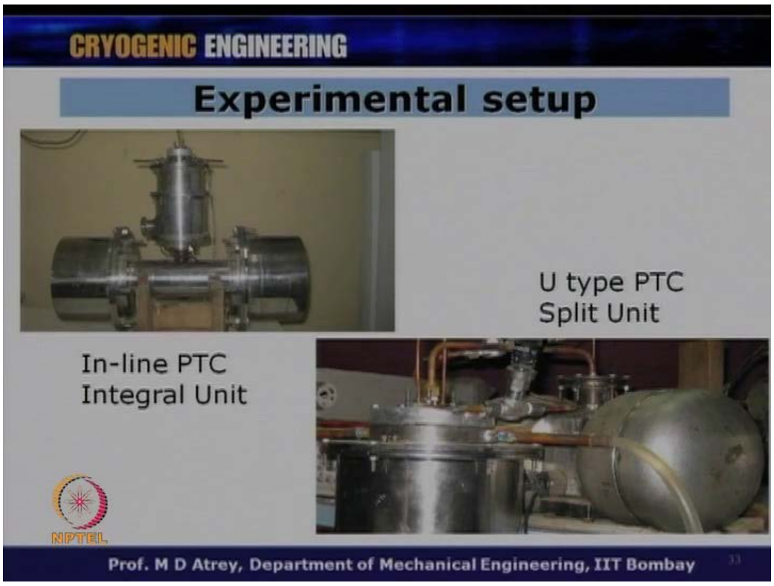

So, let us see the compressor and the pulse tube heat exchanger, in the pulse tube cryocooler and you can see (( )) inline pulse tube cryocooler mounted on the heat compressor developed at IIT Bombay. So, this is compressor on which I have kept inline pulse tube cryocooler; this is develop by one of our P h d students at IIT Bombay, and this is inline pulse tube cryocooler and integral unit, because the compressor and pulse tube cooler are attached to each other directly. There is no gap, there is no connecting tube between the compressor and the pulse tube cryocooler.

While on this unit, you can see that this is the compressor. And this is connected through a tube and therefore, this is a split unit. compressor and the expander are away from each other; they are connected through a tube, and inside this what you have is the U tube pulse tube cryocooler which you cannot see right now, but you have seen earlier and you can see the water coming over here, and cooling from this side and leaving from this side.

Similarly, in this case also you can see the hot end. hot end is going to be coming as the top, while the after cooler is going to be coming over here. In U type, the hot end and after cooler coming the same side, because there is the U connection alright. And therefore, water can cool both after cooler as well as, the hot end heat exchanger in the same direction, but here it cannot do that thing, the after cooler is here while the hot end heat at the other end.

And the top end comes the inertance Tube. So, I have not shown, you cannot see the inertance tube over here; similarly, I will have inertance tube coming from the hot end of the pulse tube cryocooler in this case.

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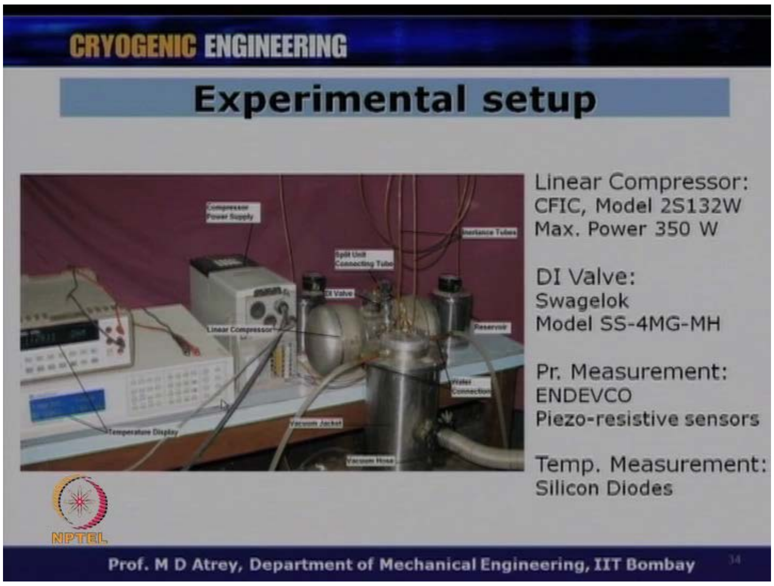

Now, this is the complete experimental set of you can see, and here I have got a compressor, I have got a expander or a vacuum jacket and you can see the inertance Tube, opening into a reservoir at this point. So, I have got a linear compressor here, from CFIC company; I have given the model, it can give power of 350 watt. Then, I have got it power supply, then I have got other units, I have got a double inlet wall used over here, I have got a pressure measurement sensors (( )) endevco pressure sensors have been use at this point, it is piece resistive sensors and I have got a temperature measurement, you can see this is the leisure temperature measurement device, and what sensor we have use is silicon diode to measure the cold temperature.

So, this is my power supply to the compressor, I can change the Frequency of this power supply also; this is the expander, a vacuum jacket which (( )) is the pulse tube cooler, this is the compressor, inertance tube opening into reservoir while this is my leisure device to measure the temperature on the using silicon diode; and these are also a temperature measurement, if I am using PT 100 as a temperature sensing device. This is entire Experimental setup would look like on a pulse tube cryocooler.

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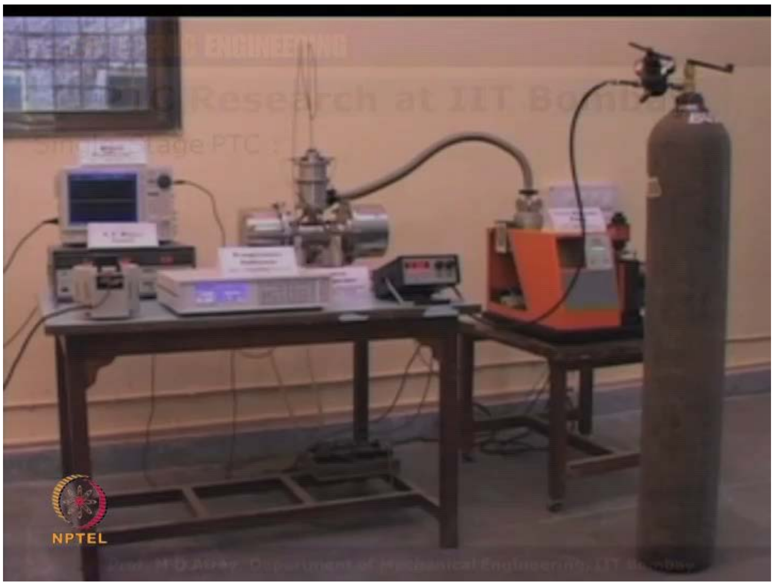

So, here I got a small video of the pulse tube refrigerator that has been developed in our laboratory. Our past research student (( )) narayan (( )) also has worked towards making this pulse tube refrigerator at IIT Bombay. So, this my pulse tube refrigerator, and this is the linear compressor.

Now, I am charging some gas from the gas cylinder to this pulse tube refrigerator. Now, use turbo molecular pump to vacuum out, the vacuum jacket; which is across the pulse tube refrigerator in which the pulse tube refrigerator. This is my pulse tube refrigerator, and this is the vacuum. You can see, I have use a K f coupling to connect this Vacuum hose in this vacuum jacket; this is my linear compressor in which the Single Stage in line pulse tube refrigerator, this is the hot end of the pulse tube and this is the after cooler which is what we there the again, the water is circulated to remove the heat of compression alright.

So, you can see this Vacuum connection, and this is by temperature measurement; this is the power supply, I am giving some 100 watt power supply to begin with and this is the oscilloscope here in, I see the pressure fluctuations. We can see the pressure fluctuation now here; as soon as the power is given, this is around 102 watts are (( )) actually, and you can see that the pulse tube refrigerator has started functioning, temperature is coming down to 251 kelvin and power is just 100 watts, and you can see a pressure pulse monitored at this point at the hot end of the pulse tube.

So, we got a various instruments here, this instruments monitors the charging pressure or the filling pressure over here; you got a turbo molecular pump here used for Vacuuming the Vacuum Jacket; and this is the inertance tube of the pulse tube alright. You can see this is the power supply, which gives you are on 100 watts at 50 hertz alright. So, I am giving power supply at T (( )), and now temperature around 120 to 182 kelvin may be after 5 to 10 minutes, and now it has come to 100 kelvin, 91 kelvin.

And now the power was increased 200 or 160 watts, and now increase the power to higher values. And correspondingly the pressure ratio will increase, and the temperature will start coming down, it has come to 82 kelvin; now for, 205 watts power input. It has come to 78 kelvin now. So, we increase to from 100 to 200 to 250 and now, the power is 300 watts. And temperature of 48 kelvin has reached; this is the lowest temperature that we could be achieved by this Single Stage Inline pulse tube refrigerator developed in our laboratory at IIT Bombay.

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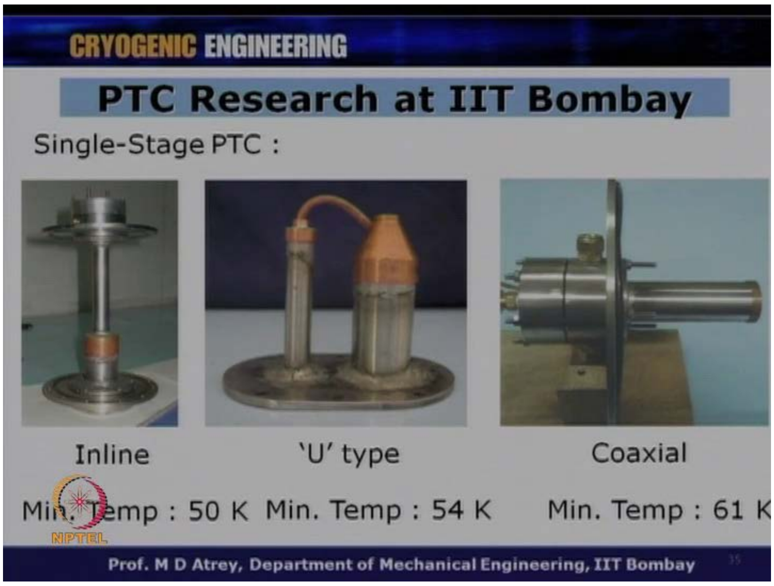

Now, I would like to show different fabricated parts of the Single Stage pulse tube cooler. For example, this is the Inline pulse tube cryocooler alright. So, you got a Inline pulse tube cryocooler, the regenerator and the pulse tube cooler are Inline which each other, this is the hot end after cooler, this is the hot end the pulse tube.

Let us see this fabricated part here in this camera, please see this part. So, you can see this part over here; I have just show you picture of this. So, the gas will enter from here, and I will have lot of meshes mounted over here which basically form the regenerator; the gas will go through this regenerator which has got mesh material put over here, which acts as the matrix material at this point, I will also have a cold end heat exchanger sitting over here; which is in direct contact with this.

So, whatever I want to cool, I will cool with this. So, this is Inline unit, in which you know that the cold end heat exchanger is at the center; leading into pulse tube cooler here. Leading into pulse tube and pulse tube opens at the hot end the pulse tube. So, I will have a hot end heat exchanger on other side forward by inertance tube coming on this direction.

So, this is the simple pulse tube Inline, while the regenerator and the pulse tube are Inline, the cold end heat exchanger it at the center. Also, I would like to show right here, what is this regenerator. So, in this now, coming back to the same system, I got a regenerator meshes over here. So, you can see this regenerator mesh; you should focus on this, this is my regenerator mesh and this is the 400 size; that means, I have got 400 mesh in 1 inch; I have cut it from a cloth of stainless steel, and I have made it I have punch them in this size, you have to do dye and punching for this, and all these things are you know 1000 of these put together, they have to be inserted in these through which the gas flows, and the gas gives this heat to the matrix or this meshes basically store the heat.

So, this is a very important how the meshes are (( )) this is a most important component, because if your meshes are not could, if there does having does they will not be good flow of the gas. And this mesh is connected from a cloth, and this is the cloth a simple cloth. So, we can by meshes from the market, and it is like this I can put them together, and I can cut meshes from here; I can fold this cloth and then I can have a punch like this and then from which I can generated the punched mashes like this, for whatever diameter you want. So, that it fits in the regenerator. And this is the most important operation.

You can see that is a very fine mesh; 400 meshes in 1 inch. So, you can see that dust sometimes can get occupied, can occupy the space over here. And therefore, it will not allow the gas to flows. So, it has to be absolutely properly clean normally, this operation in a commercial organization will be done in a clean rooms. So, that dust will not be there.

So, this is my Inline pulse tube cooler. And now I will show you U type pulse tube cooler. So, this is my U type pulse tube cooler; and with this cooler we have got Inline cooler we have got 50 kelvin temperature, U tube pulse tube cooler we got a 54 kelvin temperature, and I have got a coaxial pulse tube cooler also which we have got around 60 kelvin temperature

So, I will show you all this 3 parts. So, let us come back to this camera again. So, this is my Inline pulse tube cooler alright. Then, I have got a U type pulse tube cooler. So, we can see that the gas will enter through this regenerator, this is the gas enters a compressor then it comes like that and with U connection, it enters the pulse tube cooler. So, we can see in U type pulse tube cooler, the after cooler will be here and the hot end of the pulse tube cooler cooler will be here, while it will not be. So, in this... So, you can see and compare both, and this is my cold end heat exchanger; whatever I want to cool I can connect. So, this I had done in order to connect something to cool something here. So, we can see that how the cold generator is going to be transferred and whatever object I want to cool, I will kept connected to this.

So, this is my Inline connection, Inline pulse tube cryocooler; this is my U type pulse tube cryocooler. And now, I have got 1 more which is a coaxial pulse tube. So, you can see now a Coaxial pulse tube can you see this. So, the annulus part you can see is the regenerator in which, I will fill the mesh. So, the gas will come and go through the annular part, and it will come through regenerator out now. So, at the bottom end where my heat exchanger is going to be there the gas will turn like this.

So, we can see how compact this unit is if you remember my earlier, I had said that the user will always love to have a very compact unit, and it offers a lot of heat transfer area at the bottom to be cooled this is my cold end, but construction wise is a little problem the fabrication is always a problem; and also the pressure drop across is a very large pressure drop. So, although I prefer to have a coaxial pulse tube cooler; the fabrication wise is a problem, and now you can see all 3 units over here. You can see a Inline unit, the heat exchanger at the center the cold end heat exchanger at the center the U type and the coaxial unit.

So, I will show you all the parts which are fabricated, and now let us come back to our slides to see the results.

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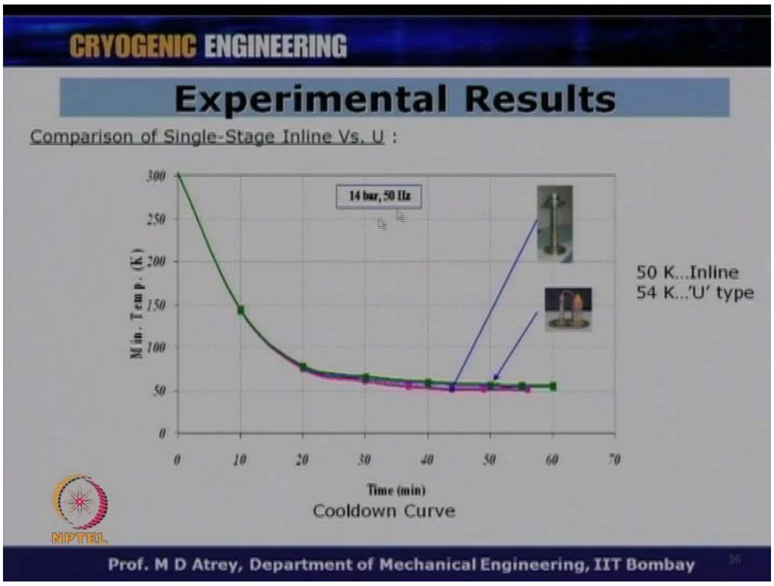

So, now let us see the results for the Inline the U type and coaxial type. Here you can see, I have plotted temperature verses cool down curve verse a time, and you can see that with Inline temperature I could reach 50 kelvin, and the temperature reaches to lower value within half an hour you can see or 40 40 minutes, while U type unit I have got 54 kelvin, and you know the fact as I said earlier, the gas thermodynamically always prefers you know it travels a same direction therefore, the pressure drop (( )) are minimum, while you have to gases to take 180 degree term and therefore, the pressure drop (( )) are more and therefore, the temperature in this case has not reach to as low as what we got in a Inline unit.

So, we got a 14 bar charging pressure in this case and operation is done at 50 hertz. What we have reach 50 kelvin for Inline and 54 kelvin for U tube, and this is what is called as cool down curve.

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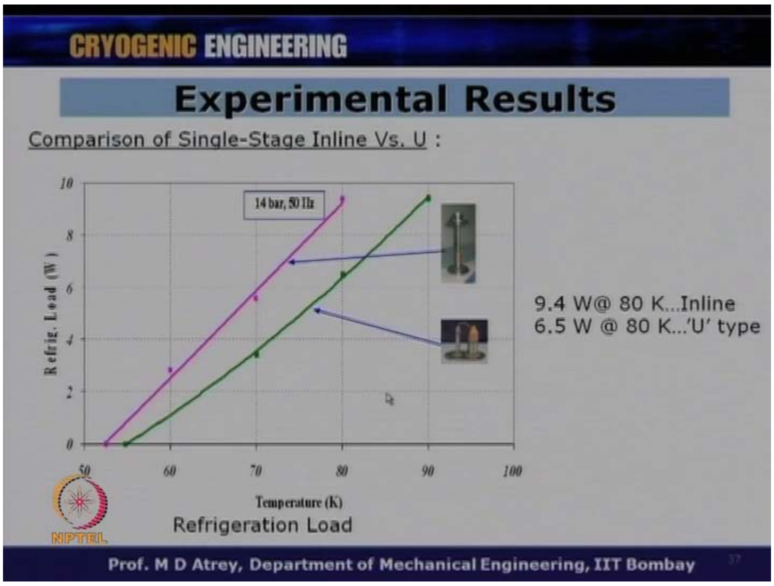

Now, I (( )) want to see the cooling effect also. So, what I do normally I will put a electrical heater at the other end or the cold end; and I will go on increasing the wattage which will actually acting as the dummy load in a system, and this will give you basically what is the wattage or a cooling load delivered from a system.

For example, at 80 kelvin I can see that I got around 9.4 watts at 80 kelvin, and this is what we call as a cooling load. The cooling load is always be associated with some temperature, while U tube pulse tube cryocooler, I have got 6.5 watt at 80 kelvin. Again showing that some cooling effect is loss, because the pressure drop and increase the dead volume at the cold end; so, I get around let say 10 voltage 80 kelvin for 14 bar charging pressure and 50 hertz operation.

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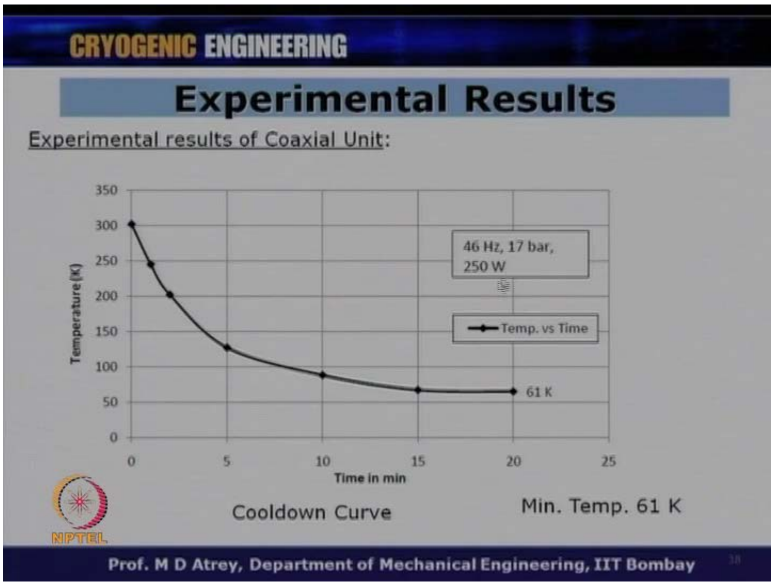

And now, I have got a coaxial unit again here; I reach around 61 kelvin temperature, but you can see how fast I have reached here. Basically, in almost 20 minutes, so I have got a operation at 46 hertz, but I got 17 bar higher pressure little bit as complete to earlier case, and power input of 250 watts.

So, these are my different results; I will just wanted to show you various results, how are they plotted, and we can compare the Inline versus U versus coaxial. As I earlier told, you Inline is always beneficial from thermodynamic point of view, but it has got the cold end heat exchanger at the center U type, and the coaxial will be preferred, but in co axial unit the fabrication is a problem, but the unit is always very very compacts. So, normally the U type pulse tube cryocooler is normally manufactured by most of the fabricators right.

Having seen, all this parts having seen the summary having seen sorry having seem all the theory behind the pulse tube cryocooler; the stirling cryocoolers the GM cryocooler , the stirling type machines stirling type pulse tube cryocooler ,the GM type pulse tube cryocooler; I would now ultimately would like to take, you to the summary of the all the lectures of this cryocoolers. So, summary is let us go step by step.

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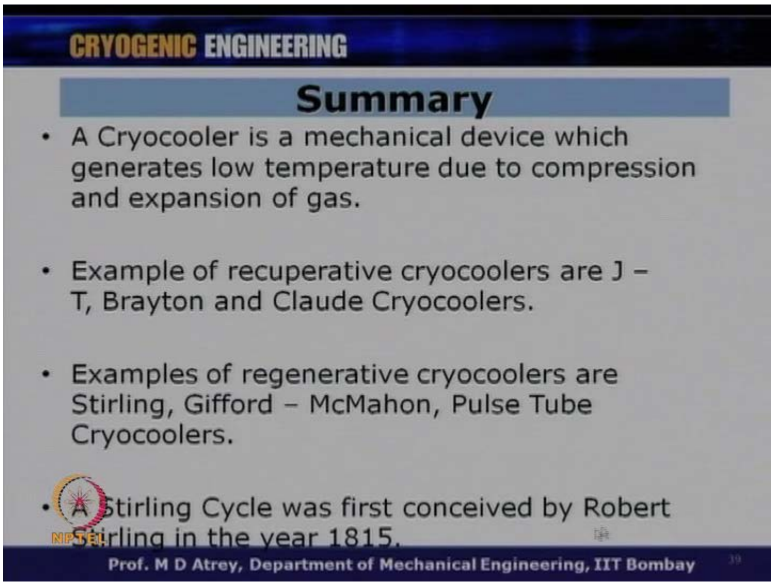

A cryocooler is a mechanical device which generates low temperature, due to compressor and expansion of gas this is what we have understood. The example of recuperative cryocoolers are J-T cryocoolers brayton, cryocoolers claude, cryocoolers they use recuperative heat exchanger, and not Regenerative heat exchangers. The example of regenerative cryocoolers are stirling cryocoolers gifford mcmahon crycoolers, and pulse tube cryocoolers, a stirling cryocoolers was first conceived by robert stirling in 1815.

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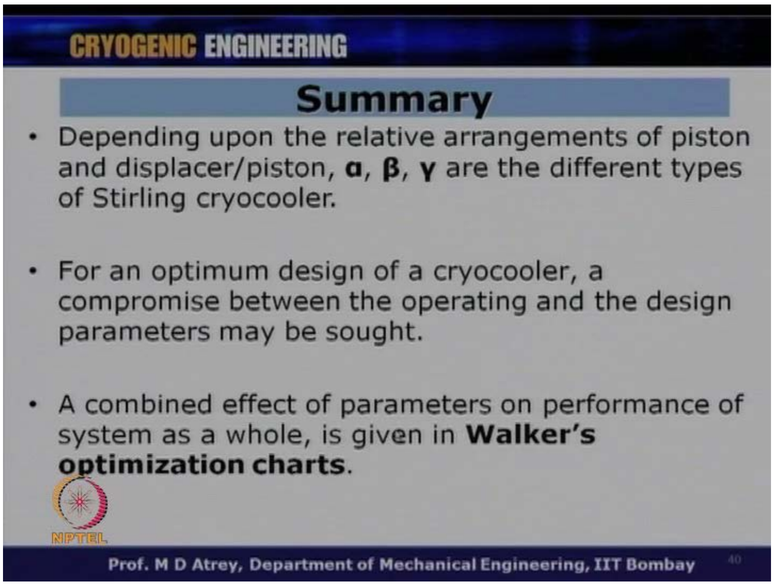

Depending upon the relative arrangements, depending on the relative arrangements of piston displacer piston; we had alpha, beta, gamma combinations possible and depending on the Geometry of this arrangement; there different types of stirling cryocooler. For an optimum, for an optimum pulse tube cryocooler for an optimum designer cryocooler; it between operating and design parameter may be sought. So, operations may demands some different parameters, the design may demands some different parameters, and you have to do optimizations based on this.

A combined effect of parameters on performance of a system, as a whole is given in walker's optimization charts. So, we had use walker's optimization chart to design a stirling cryocooler, and you can go back to those lectures to understand what was this optimization.

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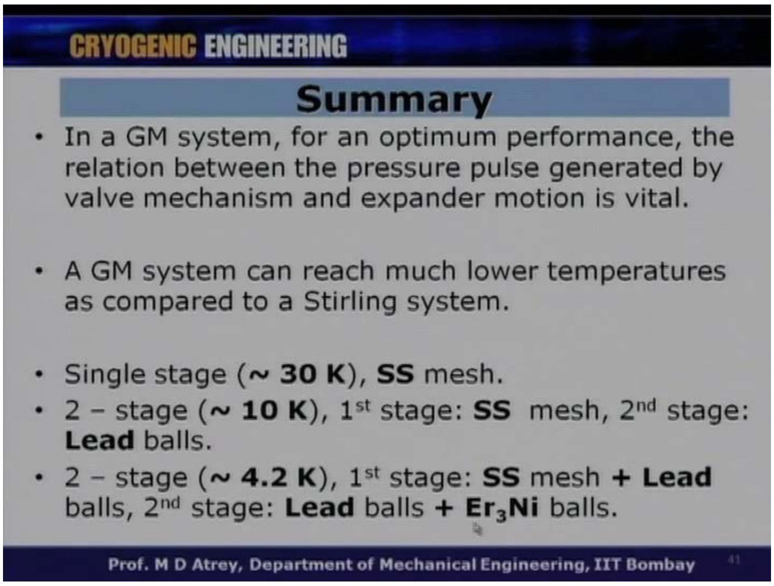

Now, in a GM system for an optimum performance; the relation between the pressure pulse generated by valve mechanism and expander motion is vital. So, we know that in a GM system, you got a valve in between the compressor and the expander. And therefore, the relationship between the pressure generated by the mechanism and expander motion, you got a displacer moving over there. And this relation is very very important while in (( )) system the relation between the system piston, and displacer is what is mostly important.

A GM system can reach much lower temperatures as compared to stirling system. Normally, in a single - in a one single stage or in two stage unit. We can reach much lower temperature, because it operates at low frquency; however, the power input required for a GM system is much higher than the stirling machines.The Single Stage normally, will reach around 30 kelvin using Single Stage using stainless steel mesh; for a Typical GM cycle while a two Stage machine can fetch (( )) 10 kelvin temperature, while which can use on the first Stage stainless steel mesh; and on the second Stage, it will leads lead balls at regenerator matrix.

Also we can get two stage reaching 4.2 kelvin temperature in which case, we will use first Stage which stainless steel mesh plus lead balls; if possible and second stage we can have lead balls plus erbium 3 nickel. This is the magnetic materials to be used in the second Stage of the material where, the CP of this material increases at very low temperature; it could be hybrid regenerator having lead balls plus erbium 3 nickel or it could be 100 percent erbium 3 nickel also.

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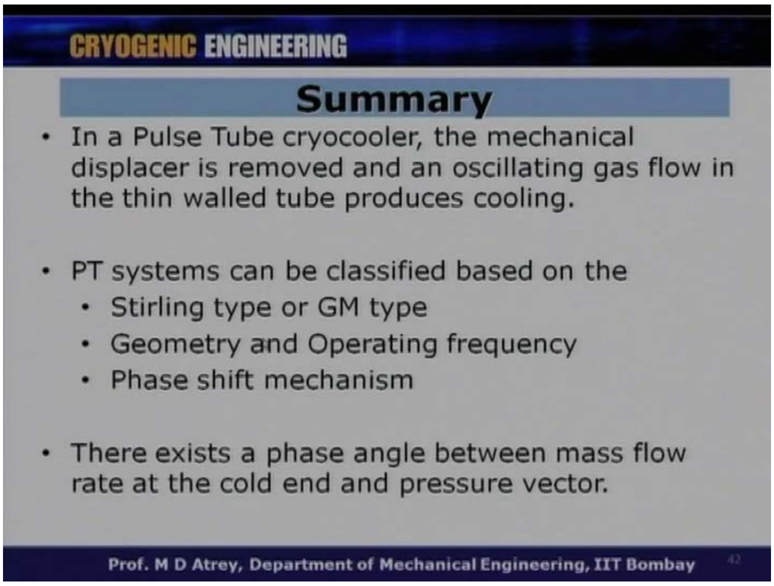

In a pulse tube cryocooler the mechanical displacer is removed, and an Oscillating gas flow in the thin walled tube produce cooling; this is what we talked about pulse tube cryocooler .The pulse tube system can be classified based on stirling type or GM type - the Geometry and operating Frequency, we know that Inline U Coaxial having high frquency , low Frequency kind of machines; we can have phase shift mechanism. So, we can have OPTCB, PTC, ITPTC, double inlet and all this things which is what we have study from phasor diagram.

There exist a phase angle between the mass flow rate at the cold end, and the pressure vector in the pulse tube cryocooler which we try to minimize for which, we employ various phase shift mechanisms.

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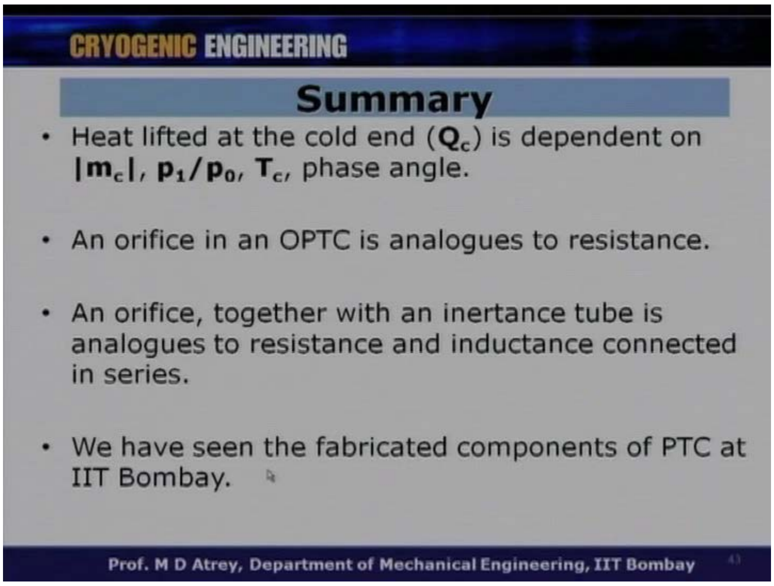

Heat lifted at the cold end depends on m dot CP 1 by P 0 TC, and phase and phase angle for a pulse tube cryocooler an orifice; in the OPTC analogous to resistance an Orifice together with inertance tube is analogous to resistance plus inductance connected in series. And this is what we have studied today using the RLC circuit, and we have seen that various units have been fabricated at IIT Bombay. We are working on 2 Stage and as well as three Stage units. In fact, we have reach around 20 kelvin no using a two Stage PT R, we have seen that we have around 50 kelvin using a Single Stage PTC. We are already started working on the three Stage pulse tube cryocooler also at IIT Bombay.

So, we have seen that fabricated components at IIT Bombay. We saw I have shown you various components of you know, after cooler hot end heat exchanger. You also seen the mesh material which is for regenerator. So, with this background, if you want to work on the pulse tube cryocooler stirling cooler, GM coolers you are most welcome and with this lectures, I feel that you can start working in the cryocooler research.

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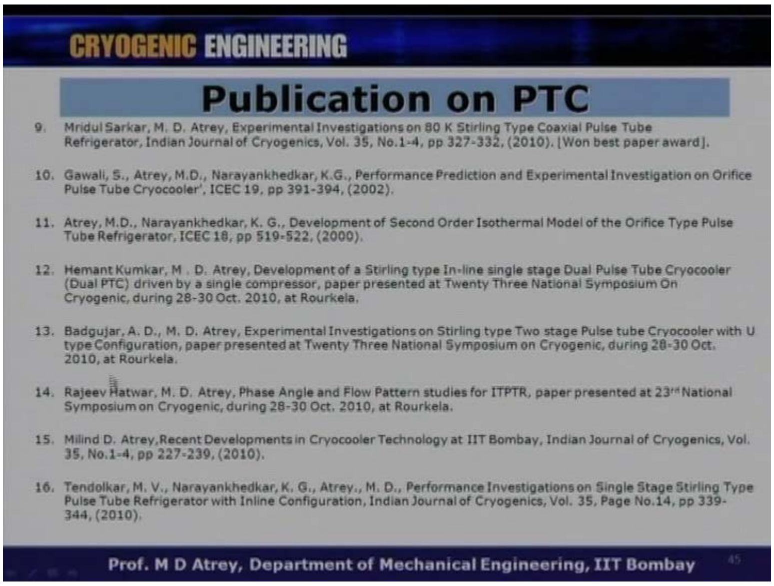

Now, various publications can be seen we have generated lot of publications, and this is what I would like to go through. So, there are publication in the conferences, and journals various journals. I have given all the details, I cannot go through all these things, but there are various lectures given in the national conferences, as well as in the internal conferences.

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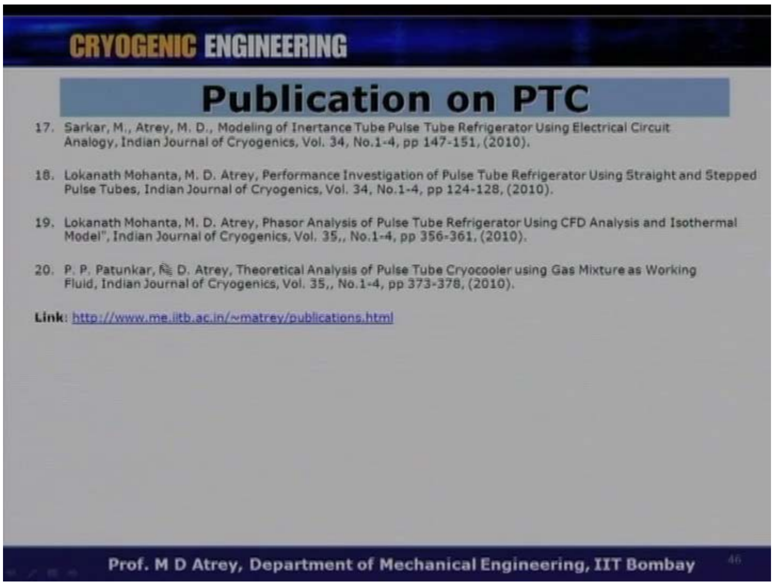

And they are all given on the website. So, this is for (( )) data; please go through those papers get access to this journals, and you can see all those publications, which will talk about, what I have developed, what I have shown you here in this lecture. Thank you very much.