Process Control and Instrumentation
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Lecture - 44
Pressure Measurement (Contd.)

In our previous lecture we started our discussion on high-vacuum measurement. So, let us continue with our discussion on high-vacuum measurements or instruments that are available for measurement of very low pressure or high-vacuum.

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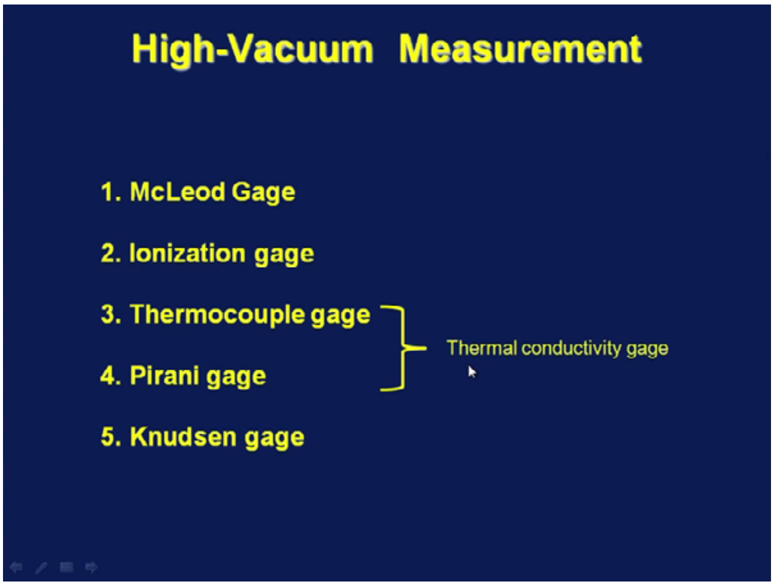

We will be talking about these five different gages that are available for measurement of high-vacuum. McLeod gage, ionization gage, thermocouple gage, pirani gage and knudsen gage. Thermocouple gage and pirani gage, they can be called thermal conductivity gage they use the same principle and they are clubbed together as thermal conductivity gage.

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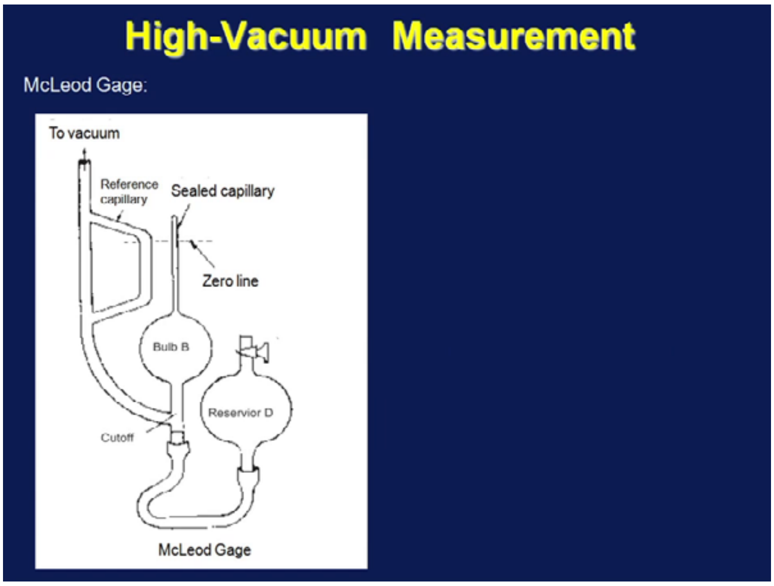

We have talked about McLeod gage in your last lecture. If you remember, this is the capillary connected to a bulb and there is another reference capillary and this is connected to the vacuum source. So, this is connected to the source whose pressure I am going to measure this is sealed. The other end is connected to a reservoir which contains mercury and this is movable. So, the measurement starts as follows. First we lower the reservoir sufficiently, so that this entire part is filled with the gas. And then we raise the reservoir, as we raise the reservoir mercury layer goes up and then when it re when it crosses this point, this part gets disconnected from this part. We continue today’s the reservoir until the mercury level in the refinance capillary makes the 0 on the scale. And then this length from the knowledge of this length, we can measure the pressure from the knowledge of the dimensions of this McLeod gage.

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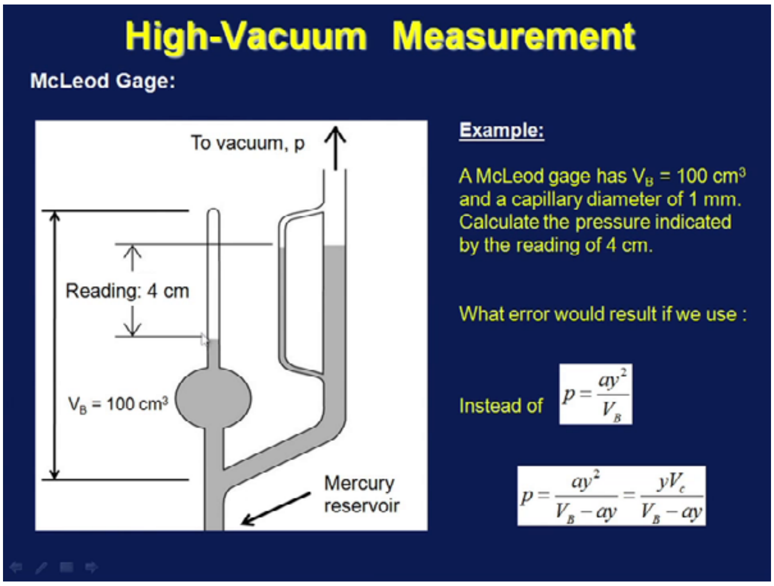

So, let us take a simple example and elaborate on this. A McLeod gage has V B equal to 100 centimeter cube, meaning the volume of the bulb, the volume of the capillary and the volume of the tube down to this point is 100 centimeter cube. And the capillary has the diameter of 1 millimeter. We need to calculate the pressure indicated by the reading of 4 centimeter. So, this reading, this is the 0 on the reference scale.

So, when this source 4 centimeter, we want to know how much pressure is indicated by the gage. In our last class we derived these equations. p equal to a y square by V B, where a is the cross sectional area of the capillary, y is this length. We have seen in our last class that the pressure can be computed from this equation, p equal to a y square by V B or p equal to a y square by V B minus a y, which is same as y into V C by V B minus a y. So, McLeod gage has volume equal to volume V B equal to 100 centimeter square, 100 centimeter cube. So, this entire volume is 100 centimeter cube and the reading is 4 centimeter. So, this is 4 centimeter.

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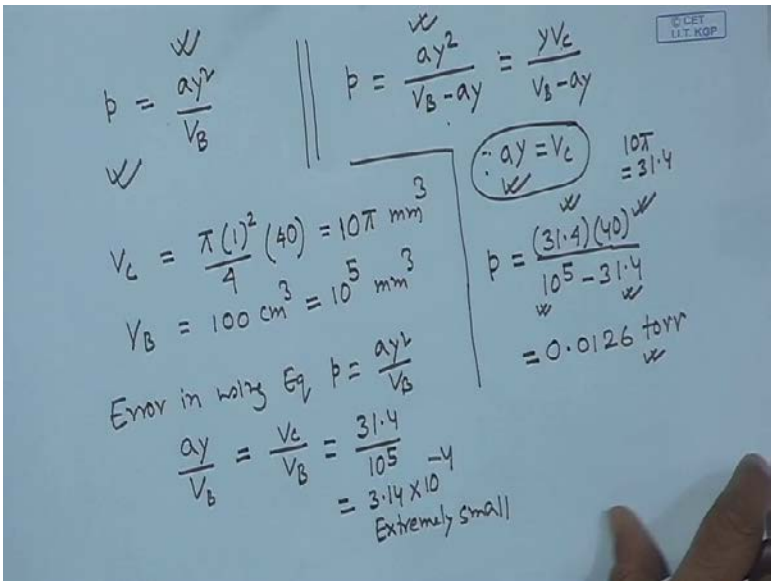

So, let us see how much pressure is indicated and this can be computed by this two equations. So, pressure can be computed using equations or which is same as. Since so, this is an approximation of this equation. Since a y is a small we can neglect a y in comparison to V B. This is the volume of the capillary. So, let us calculate first V C 1 millimeter diameter. We have 4 centimeter reading. So, 40 millimeter. So, this becomes 10 pi millimeter cube. So, V B V C which is volume of the capillary occupied by the gas is 10 pi millimeter cube. V B is given as 100 centimeter cube which is same as 10 to the power 5 millimeter cube.

So, from this equation which is the exact equation we derive last time. We can find out p as 10 pi. So, if you take pi equal to 3.14 it will be 31.4. So, 31.4. So, y V C V B a y because V C is same as a y. If you calculate this it will come as 0.0126 torr. If you use this equation will also get a value very very close to this, in fact error in using equation p equal to a y square by V B will be which is because a y equal to V C, which is 3.14 into 10 to the power minus 4. So, the error we invite due to approximation is extremely small.

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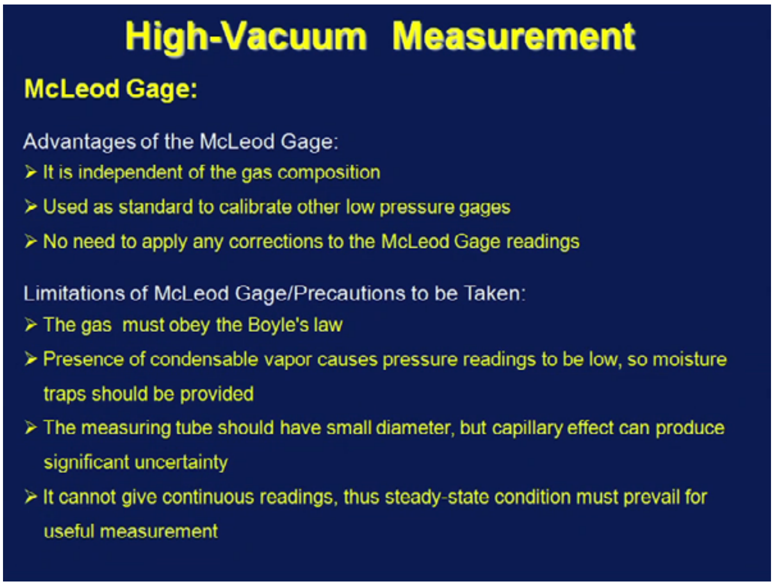

So, now let us look at some of the advantages and limitations of McLeod gages. A major advantage of McLeod gage is it is independent of the gas composition. Can be used as standard to calibrate other low pressure gages in the range over which McLeod gage can be used and there is no need to apply any corrections to the McLeod gage readings. So, it is independent of gas composition. The McLeod gage can be used as a standard to calibrate other low pressure measuring gages and there is no need to apply any corrections to the McLeod gage readings.

However there are some precautions to be taken. Since the over king of the McLeod gage is based on the compression of the gas and the gas must obey Boyle’s law. Presence of condensable vapor causes pressure readings to be low. So, moisture traps should be provided. So, there should not be any condensable vapor present because, condensable vapor occupy much more volume when their gas but the volume becomes extremely small when they become liquid. So, the presence of condensable vapor may cause great uncertainty in the reading to avoid these we must provide moisture traps.

The measuring tube or the sealed capillary tube should have small diameter, but we have to be careful that there should be any capillary effect because, if the diameter is too small there can be capillary effect and the capillary effect can produce significant uncertainty. Finally, the McLeod gage cannot give continuous readings, because the measurement involves lot of steps to be followed like the reservoir has to be lowered subsequently it has to be raised. So, it cannot give continuous readings. Thus, steady-state condition must prevail for useful measurement.

So, you must remember these limitations or McLeod gage or precautions that you must take while using McLeod gage. The gas was pressure we are going to measure must obey Boyle's law. The presence of condensable vapor can cause uncertainty in the measurement. So, moisture trap should be provided. The capillary effect should not be there. So, the diameter of the measuring tube or the capillary should not be so small that capillary effect can produce uncertainty in the reading. Since McLeod gage cannot give continuous reading, steady-state condition must prevail during measurement for useful measurement.

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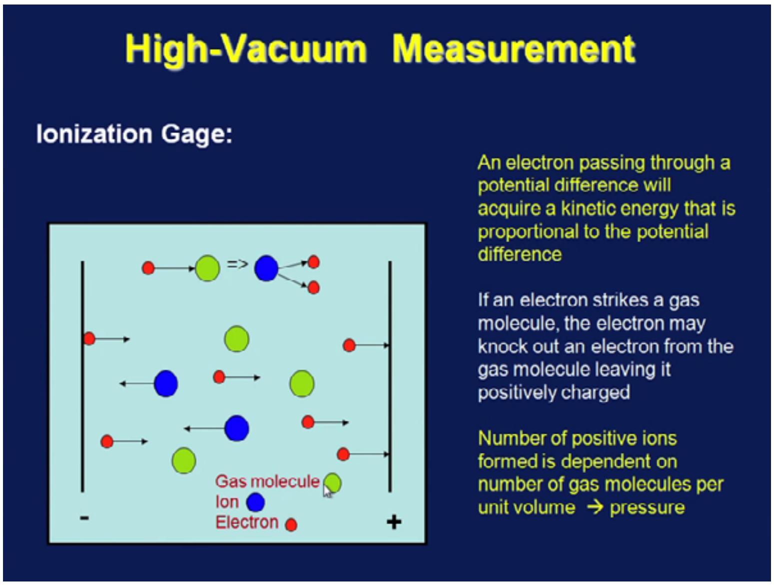

Next let us talk about ionization gage. Another important high-vacuum measuring instrument. And electron passing through a potential difference will acquire a kinetic energy that is proportional to the potential difference. Now if an electron strikes the gas molecule and this kinetic energy that it has acquired is large enough, the electron may knock out a secondary electron from the gas molecule leaving it positively charged.

Let us say we have these electrons. The red ones and these ones are the gas molecules. Now the electron are flowing through a potential difference. We have a cathode here, we have an anode here. If the kinetic energy of this electron is large and its strikes a gas molecule then there is a strong possibility, then this electron will knock out a secondary electron from this gas molecule and this gas molecule will be converted to a positively charged ion. Number of positive ions formed is dependent on number of collisions, more the number of collisions; higher is the possibility of forming this positively charged ions.

So, number of positive ions form is dependent on number of gas molecules. And number of gas molecules per unit value is nothing but a measure of pressure. So, if I saying a stream of electrons in an enclosure and enclosure is connected to the pressure source or to the vacuum whose pressure I am interested in measuring. Then this emitted electrons will strike this gas molecules and positively charged ions will be formed. Number of positively charged ions form will be depending on the number of gas molecules present in the gas, present in the enclosure which is a measure of pressure, so if I can measure the current produced by these positively charged ions. In other words if I measure this ion current, this ion current can be taken as a measure of pressure. This is the principle on which ionization gage works.

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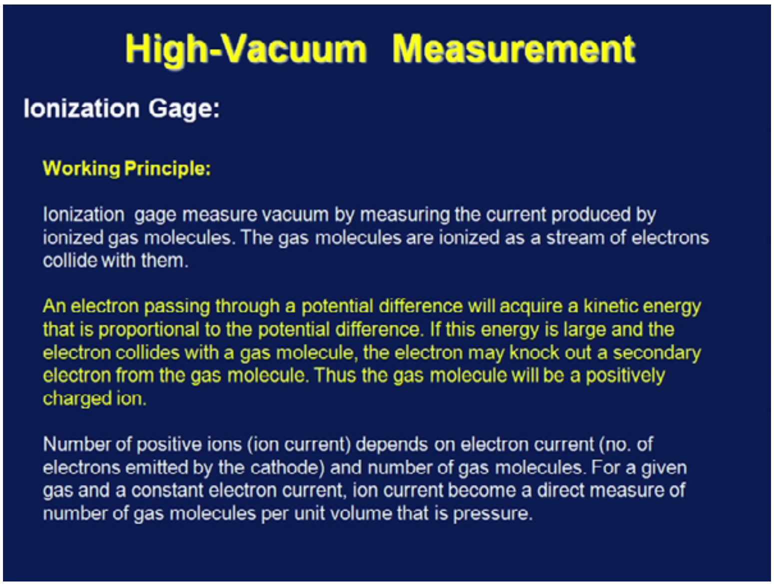

So, let us now elaborate on this. Ionization gage measure vacuum by measuring the current produced by ionized gas molecules. We can call this as ion current. The gas molecules are ionized as a stream of electrons collide with them. An electron passing through a potential difference will acquire a kinetic energy that is propositional to the potential difference. If this energy is large and the electron collides with the gas molecule, the electron may knock out a secondary electron from the gas molecule. Thus the gas molecule will be a positively charged ions. Number of positive ions in other words ion current depends on electron current that is, number of electrons emitted by the cathode and the number of gas molecules, because the number of electrons and the number of the electrons and the number of gas molecules will decide the number of collisions that can take place. So, for a given gas and a constant electron current number of positive ions or ion current becomes direct measure of number of gas molecules per unit volume which is nothing but pressure.

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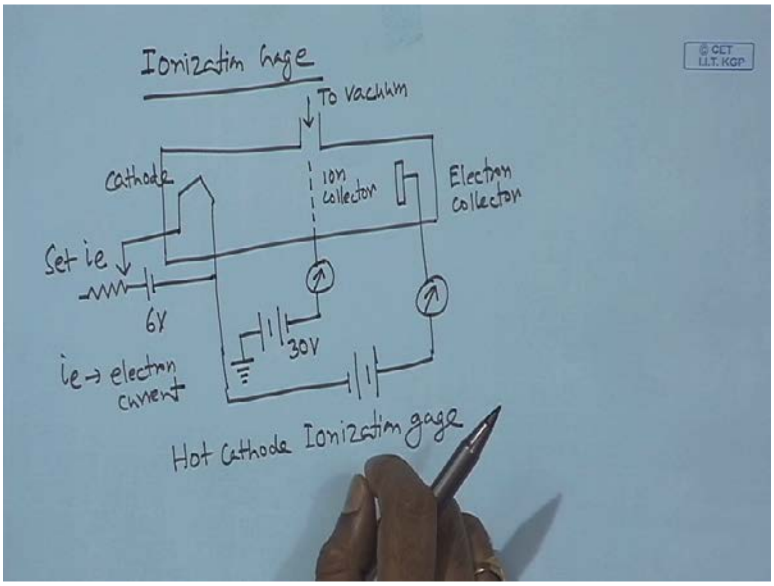

So, let us draw the circuit diagram of ionization gage, schematic of ionization gage. We have an enclosure. Let us say this is cathode, we have anode here or electron collector. So, it is anode. So, the cathode emits electrons. They are collected by the anode or the electron collector. The cathode is heated out. So, electron is emitted from this hot cathode and it is connected, it is collected by the electron collector.

This enclosure is connected to the vacuums source. So, there are gas molecules whose pressure I am going to measure. When the emitted electron strikes the gas molecule positively charged ions will be form. So, I use an ion collector. Typical value may be like this. So, emitted electrons from the cathode strikes the gas molecules that are present in the enclosure, when it is connected to the vacuum source, positively charged ions are form and they are collected by this ion collector. So, it is a positively charged grid. So, the ion current indicated by this meter, will be a direct measure of the pressure. Because number of positively charged ions form for a set electron current and given gas the ion current is a direct measure of the pressure, this is known as hot cathode ionization gage.

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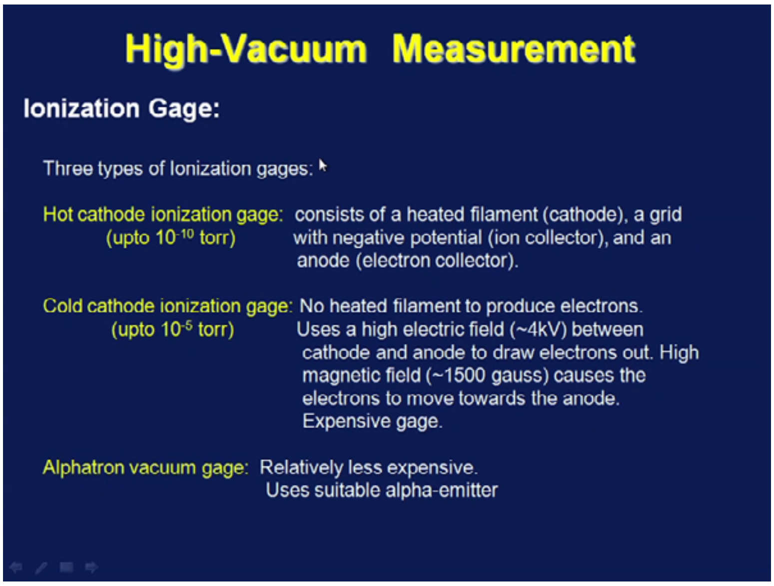

There are three types of ionization gages: hot cathode ionization gage, cold cathode ionization gage and alphatron vacuum gage. We have three different types of ionization gages. What we just discussed is hot cathode ionization gage. So, it consists of a heated filament or cathode which emits electrons agreed with negative potential which is ion collector, and an anode which is electron collector. Now, there are some difficulties associated with this hot cathode ionization gage.

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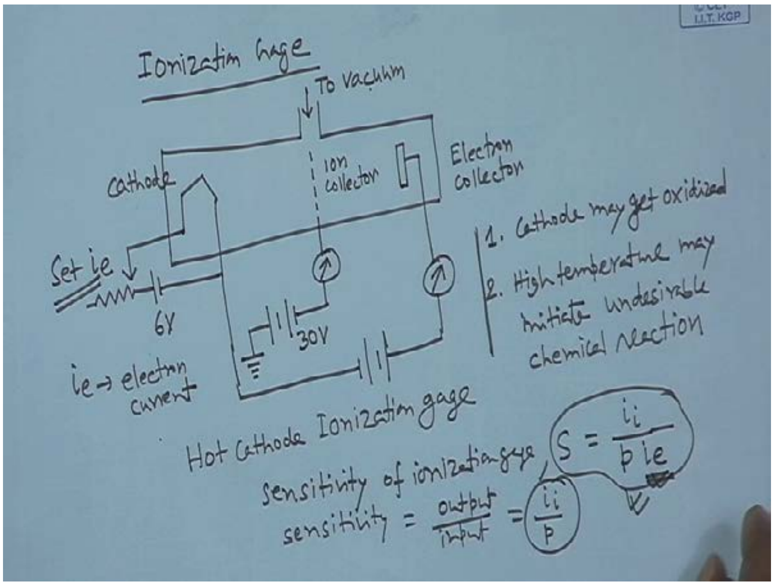

Since we are using a hot filament to emit electrons certain disadvantages arise. Number 1, cathode may get oxidized. Number 2, high temperature may initiate undesirable chemical reaction. So, to avoid these problems a cold cathode ionization gage has been proposed. In case of cold cathode ionization gage no heated filament is used to produce electrons. Instead a high electric field between cathode and anode is used to draw out electrons. Then a high magnetic field of about 1500 gauss is imposed which causes the electrons to move towards the anode in a spiral way.

So, in case of cold cathode ionization gage no heated filament is used to produce electrons. We use a high electric field of about 4000 volt or 4 kilo volt between cathode and anode to draw out electrons. And then a high magnetic field of about 1500 gauss is imposed which will cause the electrons to travel towards the anode in a spiral path. So, the path of the electron will be extended and that will increase the possibility or probability of collisions between electrons and gas molecules and thus positively charged ions will be form.

The cold cathode ionization gage is; however, more expensive. The hot cathode ionization gage can be used to measure vacuum as low as 10 to the power minus 10 torr. Cold cathode ionization gage can be used up to 10 to the power minus 5 torr. A third variant alphatron vacuum gage uses an alpha-emitter say a radium source to ionize the gas molecules.

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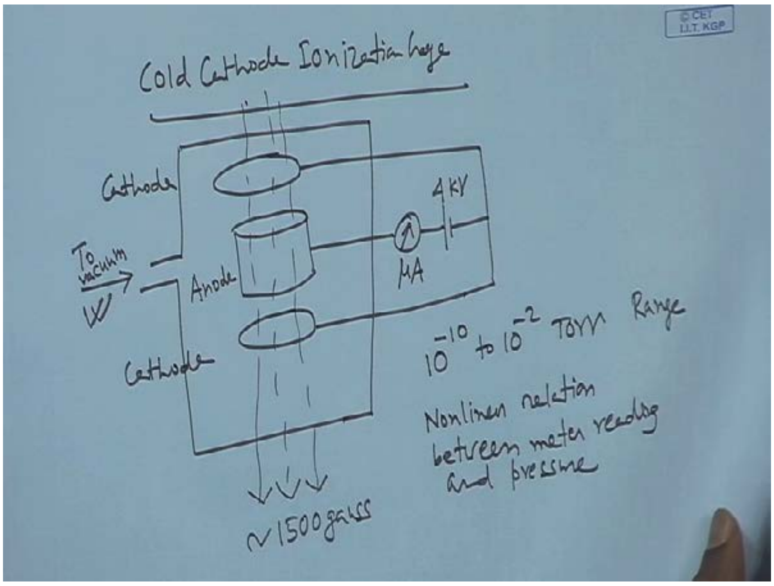

Let us now look at the schematic of the cold cathode ionization gage and alpha term vacuum gage, before that let us talk a line about the sensitivity of the ionization gage. The sensitivity of the ionization gage typically represented by ion current in the numerator and pressure times electron current in the denominator. This is unusual definition because our usual definition is sensitivity is output by input. Output is the ion current and input is of course, the pressure. But instead of using this we use this. We multiply the denominator by the electron current. This definition make the sensitivity independent of electron current and thus, the sensitivity depends only on the gage construction. We must remember the sensitivity varies from gas to gas.

Now, let us look at schematic of cold cathode ionization gage. We have cathode, we have pair of a cathode and a hollow anode. This is the enclosure, connected to vacuum source. So, high electric field of order of 4 kilo volt is applied to draw out electrons and a strong magnetic field of about 1500 gauss is imposed around the tube which will cause the electrons to move in a spiral path to the a anode. So, this increases the electron path length and thus the possibility of the collisions and formation of the positively charged once increases. The reading from the micro ammeter will indicate the pressure. The cold cathode measures a pressure between 10 to the power minus 10 to 10 to the power minus 2 torr.

So, this is the normal range of cold cathode ionization gauge; however, we have non-linear relation between meter reading and the pressure.

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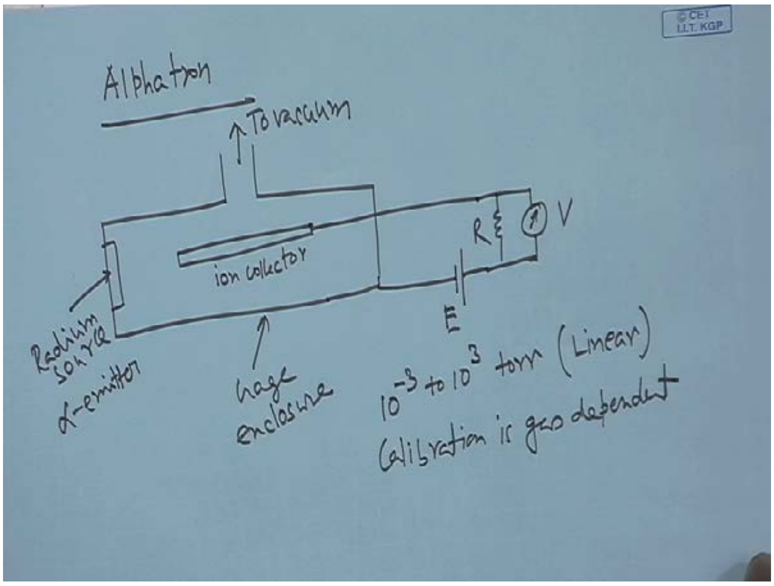

The third variant which is an alphatron uses suitable alpha emitter. So, let us say we have radium source here, alpha emitter. The alpha verticals will ionize the gas. So, we have ion collector, gauge enclosure connected to vacuum. The degree of ionization is a measure of the pressure as usual and the degree of ionization is indicated by voltage output. The alphatron has a linear range between 10 to the power minus 3 to 10 to the power 3 torr. Here the gage is linear; however, calibration is gas dependent.

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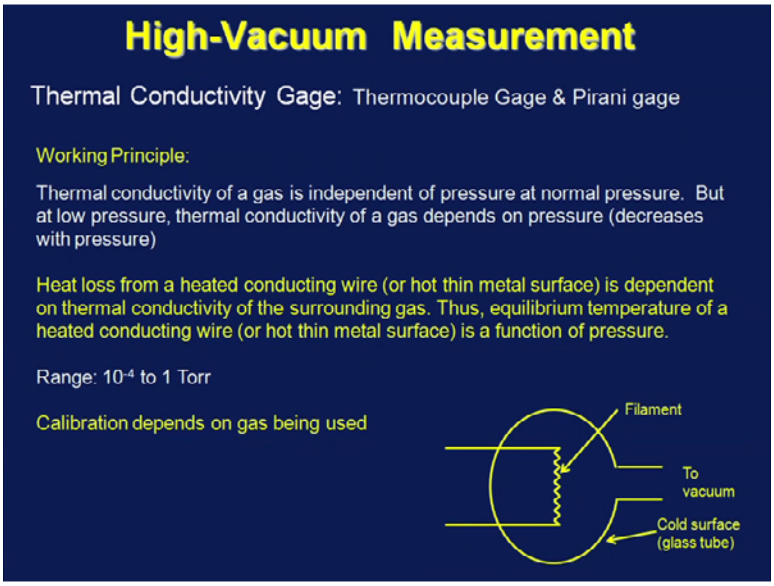

Let us now talk about thermal conductivity gage. Thermocouple gage and pirani gage come under thermal conductivity gage. Both thermocouple gage and pirani gage has the same working principle. The thermal conductivity of a gas is independent of pressure at normal pressure, but at low pressure the thermal conductivity of a gas does depends on pressure in fact at very low pressure the thermal conductivity of a gas decreases with pressure.

We know heat loss from a heated conducting wire or a hot thin metal surface is dependent on thermal conductivity of the surrounding gas. Let us say we have a glass enclosure is connected to the pressure source and we have a heated filament here. Or you can also consider it to be a thin metal surface. Now this glass surface will work as a cold surface and this is hot surface. So, there will be heat transfer between these two surfaces and finally, the filament will assume some equilibrium temperature.

Now, the heat loss from this conducting wire is dependent on thermal conductivity of the surrounding gas. And the thermal conductivity is a function of pressure when we are talking about very low pressure. Thus, the equilibrium temperature of this heated filament becomes the function of this pressure. Let me repeat again, the thermal conductivity of a gas is usually independent of pressure at normal pressure, but at low pressures the thermal conductivity of a gas depends on pressure. It decreases with pressure heat loss from a heated conducting wire is dependent on thermal conductivity of the surrounding gas. Thus, the equilibrium temperature of a heated conducting wire becomes a function of pressure.

So, if we have a heated filament in a say glass tube and this is connected the tube is connected to the gas whose pressure I am going to measure, there will be heat transfer between this heated filament and this cold glass surface. Heat loss from the from this heated from this hot surface will depend on the thermal conductivity of the surrounding gas. So, the temperature of this filament depends on the thermal conductivity of the surrounding gas, and the thermal conductivity of the surrounding gas depends on this pressure. So, the temperature becomes a function temperature of the filament becomes a function of this pressure.

So, if I can measure the temperature of this heated filament, I can relate the temperature to this pressure. Or if I am talking about a resistance wire there will be change in resistance due to change in temperature and the if I measure the change in resistance that also can be related to the pressure. So, this is the principle on which thermal conductivity gages namely thermocouple gage and pirani gage will work.

We can measure pressures from 10 to the power minus 4 torr to 1 torr using thermal conductivity gages. The calibration depends on the gas being used. This is a schematic of thermocouple gage. For a given gas and heating current the temperature assume by the hot surface depends on pressure. So, this is what we just discussed.

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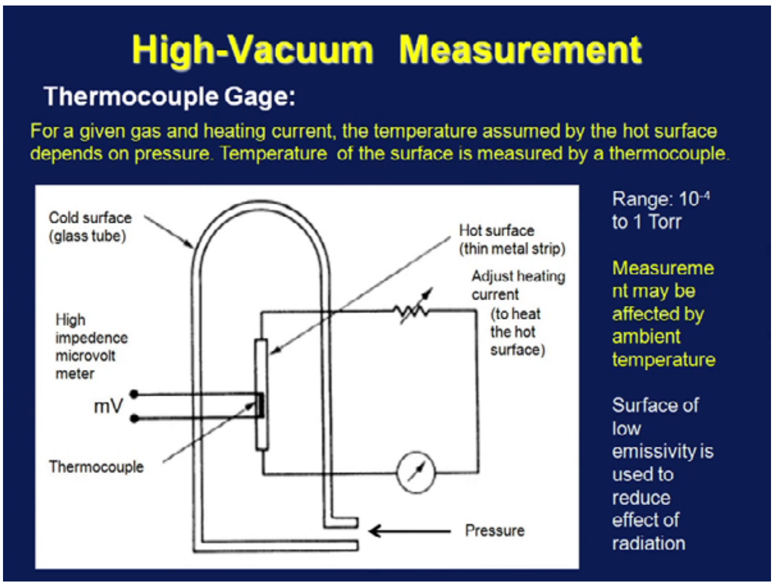

So, let us now first look at the construction of the thermocouple gage. We have a glass tube, which works as an enclosure. The pressure this is connected to the pressure source. So, this is the vacuum source. Inside the glass tube we have a thin metal strip which is heated by sending current through it. So, we can adjust the heating current to heat this metal strip at various temperatures and the temperature of this metal strip is measured by a thermocouple. We will talk about thermocouple later when we talk about temperature measuring instrument. For the time being it will be sufficient to know that a thermocouple is a temperature measuring instrument, which gives us milli volt as output. We use high impedance microvolt meter to measure the milli volt that the thermocouple gives us as output. So, this milli volt is a measure of this temperature of the metal strip.

Now, for a given gas and a given heating current the temperature assumed by this metal strip will depend on the thermal conductivity of the surrounding gas. Because that dictates the heat loss from this metal strip to this cold surface, but this thermal conductivity depends on this gas. So, the temperature of this hot metals are strip will be dependent on this pressure. So, by measuring the temperature of this metal strip using a thermocouple I can relate the temperature or the output of the thermocouple which is milli volt to this pressure. We can measure a pressure of 10 to the power minus 4 to 1 torr by thermocouple gages. Let us remember that the measurement can be affected by ambient temperature. Also, we use a metal strip of low emissivity to reduce the effect of radiation.

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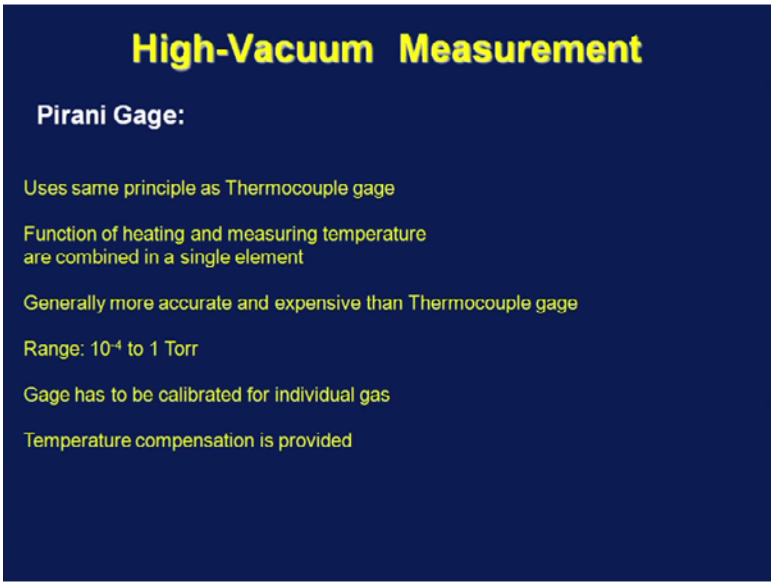

Let us now talk about pirani gage, pirani gage uses the same principle as thermocouple gage; however, here the function of heating and measuring temperature are combine in a single element. It is generally more accurate an expensive than thermocouple gage. The range is same 10 to the power minus 4 to 1 torr. The gage has to be calibrated for individual gas, because it depends, because the thermal conductivity of different gases are different. So, the gage has to calibrated for different for individual gas. Temperature compensation is provided in a pirani gage.

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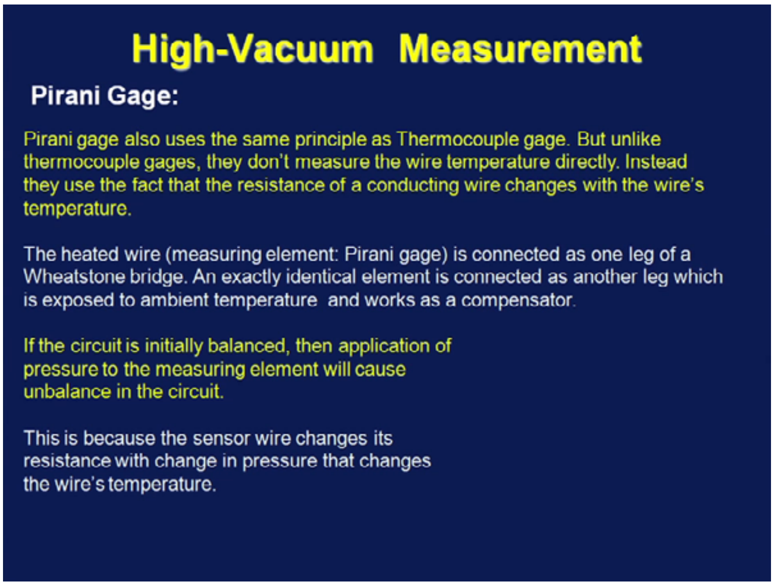

Pirani gage also uses the same principle of thermocouple gage, but unlike thermocouple gages they do not measure the wire temperature directly. Instead pirani gages use the fact that the resistance of a conducting wire changes with the wire's temperature. So, the heated wire which is let us say a measuring element of pirani gage is connected to one leg of the Wheatstone bridge. An exactly identical element with the pirani gage is connected as another leg which is exposed to ambient temperature and works as a temperature compensator.

Compensator for effect of ambient temperature, if the circuit is initially balanced then the application of pressure to the measuring element will cause unbalance in the current in the circuit. Because when we apply pressure to the measuring element, which was heated the heat loss or the temperature of that resistance wire will depend on the gas pressure. The same way this is that is exactly what we have seen in case of thermocouple gage. So, when we apply the gas to the measuring element the temperature that the resistance wire will assume will depend on the gas pressure. So, change in temperature will cause a change in resistance and the change in resistance will cause unbalance in the circuit. This unbalance current can be taken as a measure of gas pressure.

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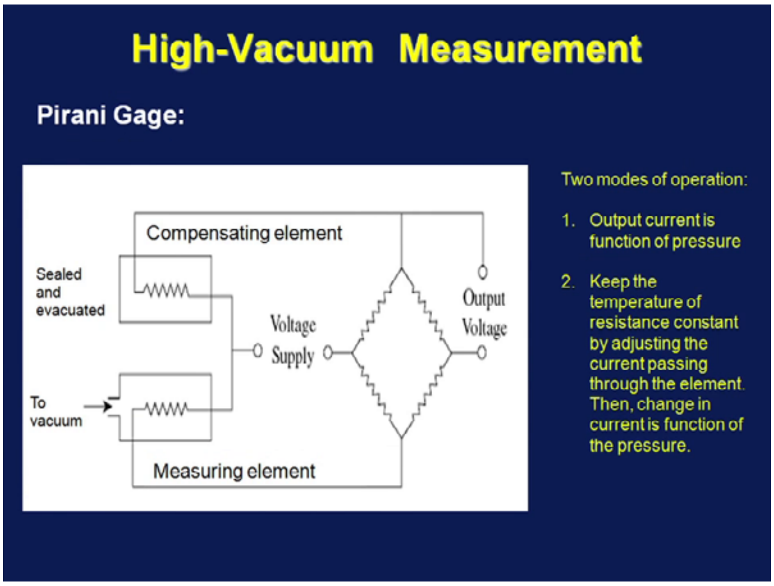

So, this is a schematic of pirani gage. We have a Wheatstone bridge. This is a measuring element, which is nothing but a resistance wire, usually platinum or tungsten wire of in times we use 4 coiled platinum or tungsten wires. The resistance wire is kept inside an enclosure, usually made of hard glass and this is connected to the pressure source.

We take exactly identical another element, completely evacuated and then sealed. So, these two are to the adjutant arms of the Wheatstone bridge. Now initially we get the null condition. Now, when the measuring element is connected to the pressure source, this pressure causes change in temperature of this resistance. If the resistance changes there will be an unbalance in the circuit. So, the bridge unbalance current will be a measure of pressure. So, initially we set, we initially balance the bridge and then the measuring element is connected to the pressure source and the bridge unbalance current is taken as a measure of pressure.

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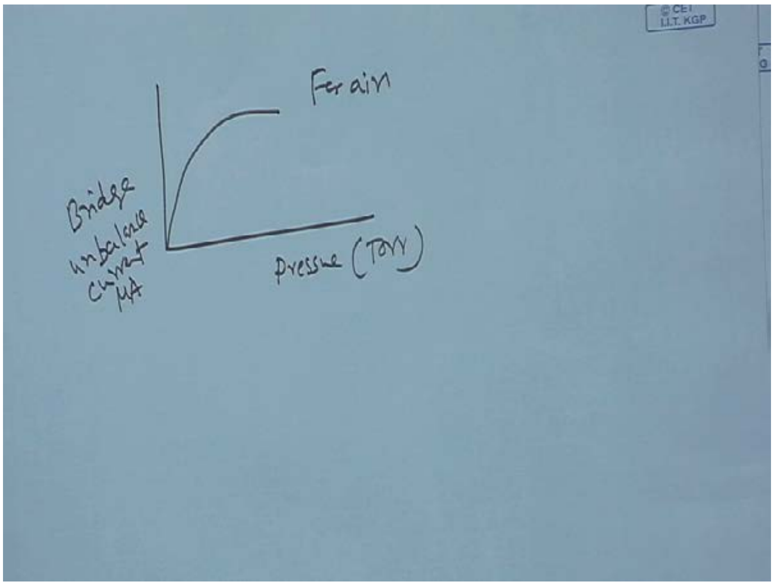

If you plug for air, we typically get a non-linear relationship. Finally, let us talk about knudsen gage. It is an absolute gage in the range of 10 to power minus 8 to 10 to the power minus 3 torr.

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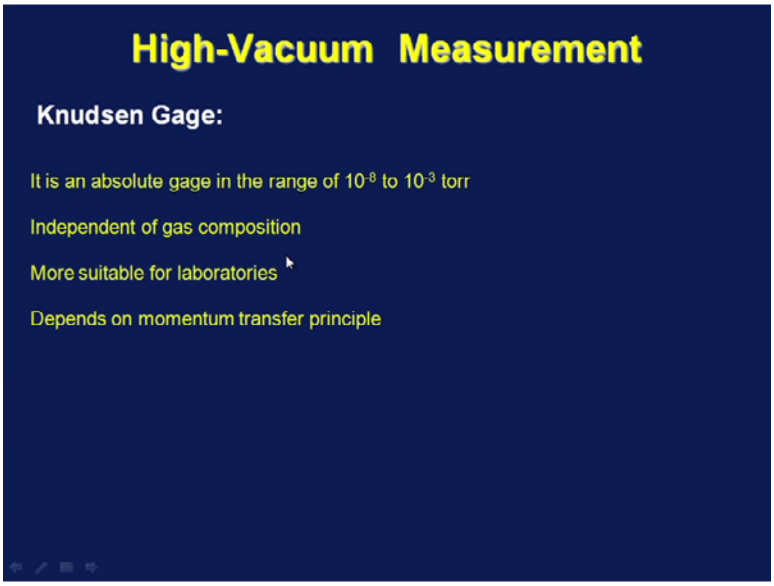

It is independent of gas composition; however, it is more suitable for laboratories. It depends on moment on transfer principle.

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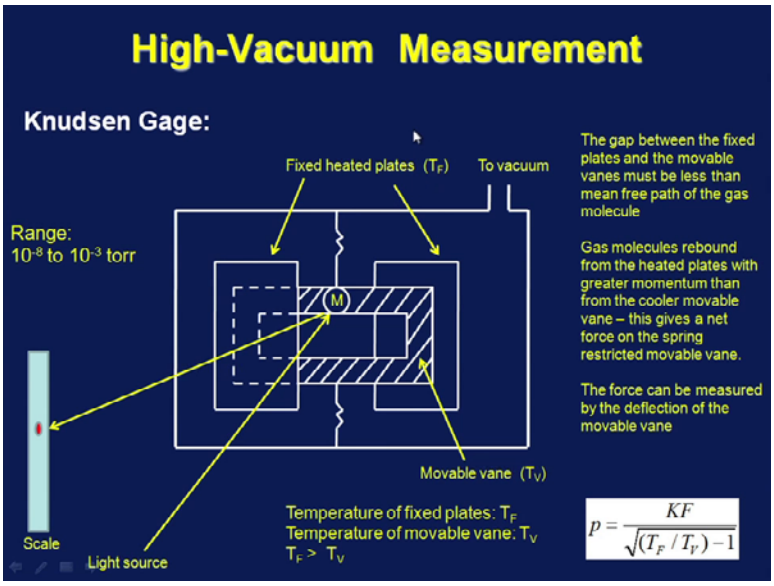

This is a schematic of knudsen gage. We have two heated plates which are fixed. In between we have a moveable vane. So, we have two heated plates whose temperature is T F, absolute temperature should be exactly known and in between we have movable vane. The gap between the movable vane and the heated in this fixed plates are extremely small. It should be less than the gap should be gap between the movable vane and the fixed plates should be less than the mean free path of the gas molecules whose pressure we are going to measure. This movable vane is spring restricted, and we put a we have a mirror on the movable vane.

Now, this is connected to vacuum. The movable vane temperature should also be known. Let us say the movable temperature T V, the heated temperature is T F and T F is of course, higher than the movable vane temperature T V. Now kinetic theory tells us when the gas molecules rebound from the heated plates, they will have greater momentum compared to the case when they rebound from the cooler movable vane.

So, when the gas molecules rebound heated plates they will be back with greater momentum then the case when the rebound from the cooler movable vane. So, this gives a net force on this spring restricted movable vane and this will cause the movable vane to deflect and that deflection can be measured if I send a beam of light to this mirror, the reflection from the reflection of a spot of light on this scale, I can measure the deflection of this movable vane and then from the knowledge of the deflection I can measure the force acting on the movable vane.

So, if I know the force I can make use of this formula to determine the pressure. Where k is the constant, F is the force, T F is the temperature of the fixed plates, T V is the temperature of the movable vane. So, with this we conclude our discussion on high-vacuum measuring instruments. We end this with a sentence on how to select operation measuring instrument for given application. It is heavily influenced by the intendment application. We know the range of the pressures over which various instruments are we know the working range of various pressure measuring instruments now.

We also have to keep in mind the purpose of our measurement. For example, if only usual infection is required then a simple manometer will do. If we need an electrical output for the purpose of control or monitoring, then perhaps an l V d T or a bourdon tube with a gage or a bourdon tube with l V d T or some other transducer is more suitable. In our next class will start our discussion on temperature measuring instruments.