Principles of Mechanical Measurement
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Module – 08
Pressure Measurement
Lecture – 1
Principles of Manometry

Hello everyone, good morning to all of you. We are back with the week number 8, where we are going to talk about the measurement of a parameter which is very common to all of you, something you have heard from very early school days, which is pressure. Pressure is a term which probably you can relate to several day-to-day common phenomenon or common activities. And of course, we are not talking about the mental stress or mental pressure; we are talking about only the thermodynamic quantity the pressure.

But, still there are several situations, where you have been introduced to this particular term or you have made use a time pressure. Most common example can be the day-to-day weather report, which you keep on hearing on the televisions or on the radios, where along with the local temperature and humidity, they also quite often mention about the pressure or may not be explicitly mentioning about the term pressure. But very commonly you can keep on hearing the terms like low pressure or depression formed in some part of the country or some part of the ocean, thereby leading to the formation of some local disturbances, may be a cyclone etcetera. And we are going to talk about that very parameter in this particular week.

Now, last couple of weeks were a bit light, where we where the total content of the week was a bit lesser, whereas we discussed about the measurement of stress and strain and also the measurement of force and torque in the previous week, but, this one probably having a bit more content. But I hope most of that part will already be known to you, I shall just be trying to emphasize on some of the associated concepts, and maybe introducing a few more.

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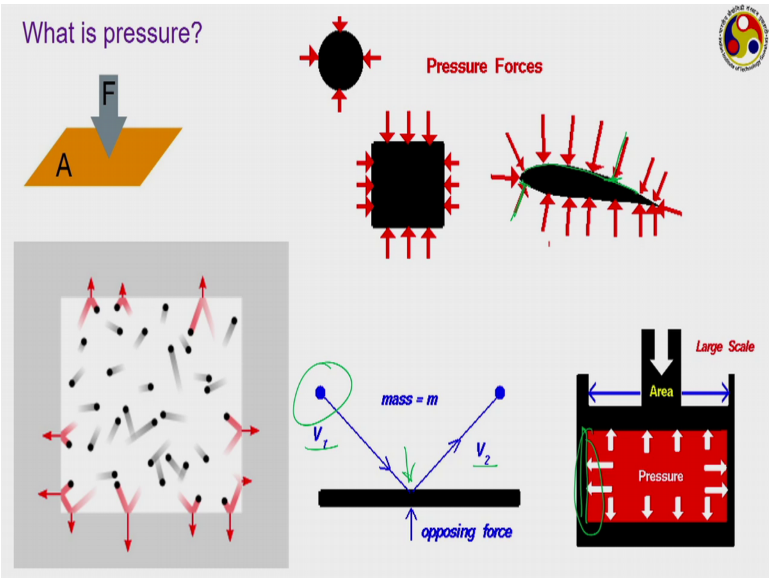

So, the first question that we have to answer is what is pressure? Now, what answer is coming to your mind, what is pressure? We all know that pressure is force per unit area, but which area should be we be talking about or which is the direction of force that we are talking about that of course we have to be very careful of, before we can go for the measurement of the pressure.

Now, if we go to the molecular level itself, then let us consider a container like this filled with certain gas molecules. Now, as per the property of the molecules, unless they are the absolute 0 temperature because of their internal energies, they will keep on moving around quite randomly throughout the entire container, thereby colliding with themselves and also colliding with the walls of the container.

And as they are colliding with the walls, if we assume if an elastic collision also, there will be a change in the momentum of this. During the collision part, they there may be a change in the velocity, so that during the collision, they will be transferring a part of their momentum to the wall or it may be possible that there may be a net change in the value of this velocity that is the magnitude of V 1 and V 2 may not exact exactly be same. Quite often, the exit velocity actually is lower than the incoming velocity, thereby causing a net reduction in the momentum of the molecule itself. And that amount of momentum will be transferred to the associated wall or to the adjacent wall.

Now, the rate of transfer of this particular momentum will definitely lead to some kind of force. So, this particular molecule as it is striking the wall at this particular position, it is putting some kind of force to this. This way all the molecules are striking the adjacent walls and each of them are putting some kind of force.

So, if we combine the cumulative effect of all this force or momentum transfer of all these molecules on a particular wall, then the force that we get that is what is associated with the pressure or the force per unit that area is the pressure means, if we pick up this particular vertical surface, then whatever momentum that has been transferred by all the molecules which are hitting this particular surface will lead to a certain force. And now, if we divide that total force by this particular area, then we get the pressure which is acting on this particular surface.

This pressure force or the force associated with pressure always has to be normal to the concerned surface. And therefore, depending upon the contour of the surface, the direction of force may keep on changing. Like the examples shown here, particularly interesting can be the aerofoil one as the surface profile keeps on changing, the direction of the corresponding pressure force also will keep on changing, because at every point the directional pressure force has to be normal to the concerned surface.

Like, if we pick up this particular point, this is the direction on the force whereas, if we pick up this particular portion of the surface, the direction is this particular one. So, depending on the orientation the direction of the pressure force will also keep on changing. And that is why while evaluating the magnitude of this pressure, we have to be very careful about which area we are talking about.

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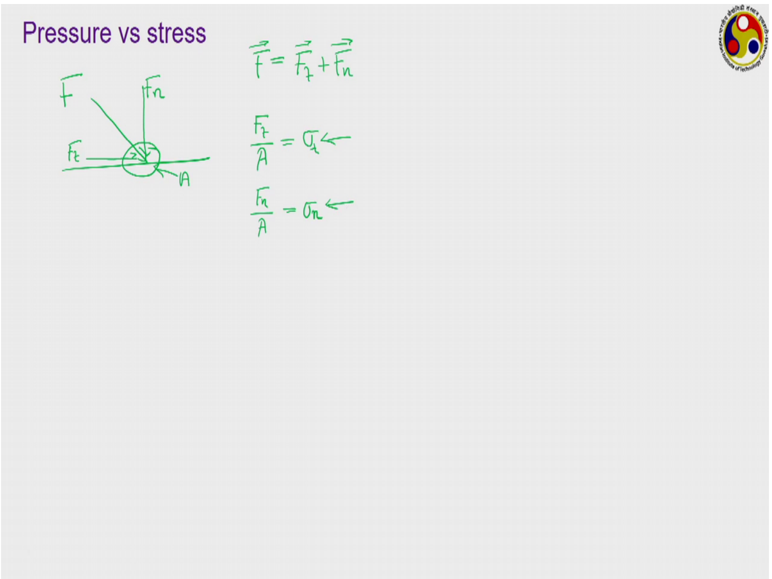

But, what about stress then, because just one week back, we are talking about the measurement of stress and strain. And you know that stress is also force per unit area. Then what is the difference between pressure and stress, both are force per unit area and then whatever way we have measured stress. The same way we can measure pressure or even more fundamentally, why you need a separate quantity at all. We could have just continued with stress itself, instead of introducing any new parameter in the form of pressure.

Now, let us say this one particular surface and a force is acting at this particular point of the surface or let me draw it in a better way. Say this is the force acting at a particular point on this particular surface, say the magnitude of the force is F. Now, if we divide this particular force or if we distribute it into two components; one normal to the wall something like this, let us say; let us call this particular as F n. And the other tangential to the wall let us say, this is F t.

Then of course, this is a vector addition. So, the total force F is a combination of this tangential component and the normal component. Now, if we take an unit area around this point of application of this force such that this area is A. Then F t by a the magnitude will lead to let us say, we write it as sigma t and similarly, F n normal component of force divided by area, let us write it as sigma n. These two other two stresses that is acting at this particular point, this one is a tangential stress, this one is the normal stress.

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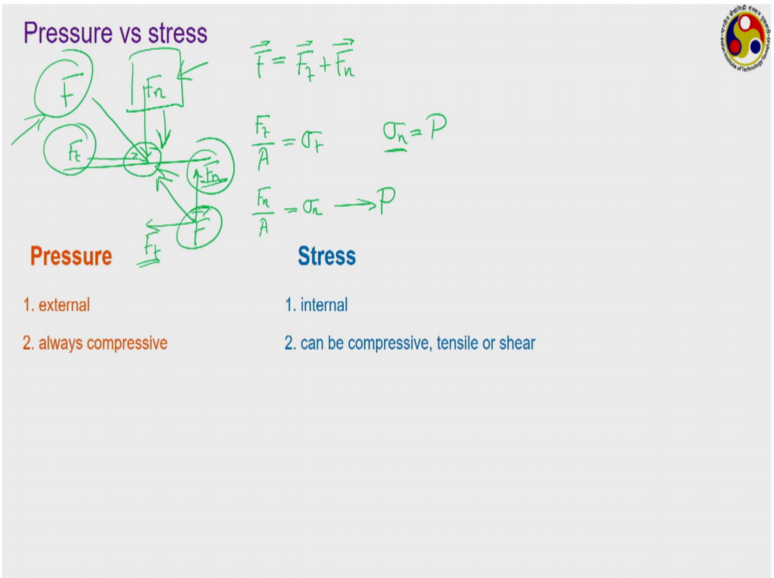

Then, what about pressure? Actually none of these poor stresses. What we have written here a force per unit area and but this particular part is not correct. Because, stress refers not to these external forces are acting on the surface rather stress refers to an internal force which is originated, when the body is getting deformed and is trying to reduce the deformation. That means; what I am trying to mean that, because of the action of this particular force F, there may be some deformation that is happening in the body, now because of its own structure the body is trying to resist this deformation.

And therefore, following Newton's 3rd law of motion, it will also produce a force of equal and opposite magnitude another force F as an internal mechanism or as a part of the internal mechanism. Now, if we divide these internal resistive forces into two components, what will be the components? The normal one will be F n itself and the nation will be F t itself, you can say that the one which is opposing this normal component of the imposed force is this one, whereas I want which is opposing this tangential component of the imposed force is this one and they have to be equal to the corresponding external counterpart.

Now, the force per unit area corresponding to these internal forces are the stresses. So, the magnitude of the tangential stress sigma t and normal stress sigma n that remains the same, because this F t and F n are same and also you are talking about the same area, but the difference is in form of senses. Here we this F t and F n are not the component of this imposed force F, rather they are component of this internally generated resistive force F.

So, stresses are internal force or part or result of internal force, which are trying to resist the deformation of the body, whereas pressure is purely an external one. And if we continue this particular diagram, then pressure actually is the normal component of the imposed force that is pressure is the normal component of this imposed force F n per unit area that is this particular one, magnitude of pressure will be this particular one itself.

However, here we are not talking about the internal component, rather you are talking about the external part. So, in purely from magnitude wise, this normal component and pressure, their magnitudes will be equal to each other. However, when this normal component sigma n, normal stress I should say refers to this particular internally normal component of this internal generate force, p refers to the normal component of this externally imposed force.

So, though their magnitudes are different, their senses are sorry, their magnitudes are the same their senses are completely different. The stress refers to the internal forces or corresponds to the internal forces, whereas pressure refers to the normal component of this externally imposed force. And another important factor is that pressure, we or rather the force corresponding the pressure will always point towards inward that is it is always compressive in nature, always pointing into the surface for this.

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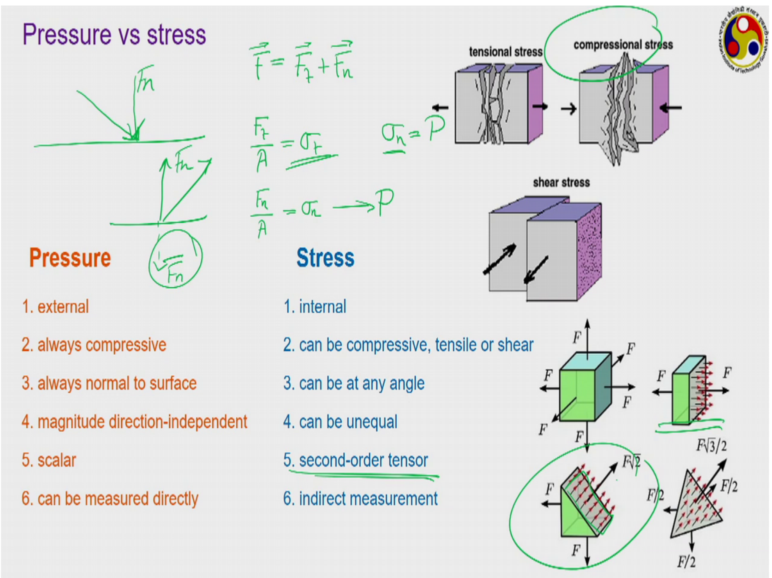

So, if we try to compare force and pressure, then of course just as I have mentioned pressure refers to the external force, where a stress is generated because of the internal forces and developed within the body to resist any kind of deformation. Pressure is always compressive in nature that is if I just clean up this particular mess of it. Then if the force is acting this way that is into the surface, then pressure will corresponds to its normal counterpart.

However, if the force is say acting outwards and its normal counterpart is this F n, then this one will not correspond to pressure, rather it is opposite. Like if we can draw something like this F n bar, let us say and these are all vectors are not putting the arrow. So, pressure will correspond to this F n bar, it is always compressive in nature always pointing into the surface that is not related to stress. Stress can be compressive or tensile or may be shear, shear actually referring to this tangential part (Refer Time: 11:37).

Like just shown in the diagram, we can have tensional stress, where the force are actually pointing outward. We can have compressive stress and we can also shear stress or the force is acting parallel to the surface, but pressure is only related to this compressional part. Then pressure forces are always normal to the surface, but as can see from the diagram stress can be at any angle.

Like we can see here, here we are having a cube and forces acting parallel to each of them. Now, if we break them, here also the surface in the second case also surfaces are parallel to each other and the forces acting normal to the surface. However, if we look at this particular case, here the force is acting here again the force is acting normal to the surface, but it is not an orthogonal direction, because here we are talking about the surface, which is not parallel to any of the orthogonal accesses. So, the pressure force will always be normal to the surface.

And magnitude is direction-independent or to be more specific, pressure is a scalar quantity. Of course, force associated with pressure is a vector like any force, but pressure itself is a scalar quantity, because at a particular point the magnitude of pressure remains the same coming from all possible directions. And that is why pressure is a scalar quantity, which does not have any direction independency. However, stress it is not a vector, it is a magnitude, it is can be unequal that is at a different. At the same point stress in different direction can be different and that is why, it is it is not a vector, it is actually a second-order tensor whereas, pressure is a scalar which can also be viewed as a zeroth order tensor.

And now, pressure can be measured directly, which you are going to learn in this course. But, what about stress, we have already learned some basic mechanisms of stress measurement. Stress cannot be measured directly, because stress is only internal to the system. What we can measure is generally strain that is deformation of a body per unit initial length scale.

And now that deformation or the strain can be related to the stress through young's modulus and maybe Poisson's ratio to get an indirect measurement of the stress. But, there is no way you can get a direct measurement of the stress, which is possible in case of pressure. Pressure we can have a direct measurement. And there are infinite number of devices, there are lots and lots of different kinds of mechanism by virtue of which we can directly measure pressure.

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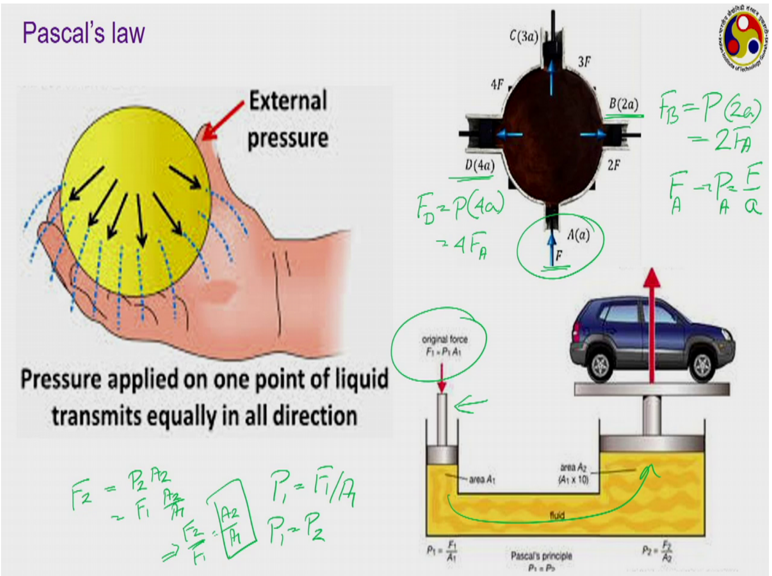

Now, that direction independency is given by the Pascal's law, which all of you have definitely learned at the school that is at a particular point on a liquid or maybe on a gas also on a fluid if we apply pressure, then force is transmitted equally in all possible direction, which essentially prove that pressure is a scalar quantity and that also has lots of applications in practice.

Like a very simple situations here, you are having a sphere just consider the sphere to be extremely small, so that the pressure remains uniform throughout the entire body of the sphere. And now there are four outlets, each having a different area. Then the force that is acting at this particular surface, if that forces F, then corresponding pressure will be force divided by the area small a. This is the pressure which is acting at point A or force, you are putting at point A.

Now, at point B that is this particular point what will be the force then, then F B pressure remaining the same should be equal to P into the area, where area is twice of a. And so if we put back the expression, it will be twice of F A. So, it is area is double, accordingly the total force is also double, because pressure remains the same. Similarly, at D here area is four times, so the force which is acting at D is again the pressure into the area of D that which is 4 of a and that is it is four times of force, which is acting at point A which is this particular one.

One possible application, you must have seen the application of hydraulic jacks, where you have a two connected cylinders filled with certain fluid, generally liquid. On one of the cylinders which is having a smaller diameter or smaller cross-section area, we are putting some kind of force like this. And that gets transmitted through in the fluid body into the other cylinder; into the piston on the other cylinder, where the area is much larger, accordingly there is a magnification of the force despite pressure remaining the same. And that we can use for doing much heavier work just like lifting a car.

So, at this particular point in this particular cylinder, the pressure which is acting P 1 will be equal to F 1 divided by A 1, where F 1 is the force that we have imposed initially. And pressure remaining the same, P 1 will be equal to P 2, so the force which is acting on the car or on the second piston will be equal to P 2 into the area of the second one which is A 2. And P 2 equal to P 1, and putting the expression for P 1, we have F 1 into A 2 by A 1 or if we write F 2 by F 1 is equal to A 2 by A 1. So, if A 2 is 10 times of A 1, there will be 10 times magnification of the force. So, this comes from the Pascal’s law which you already know and this there can be several practical applications of this.

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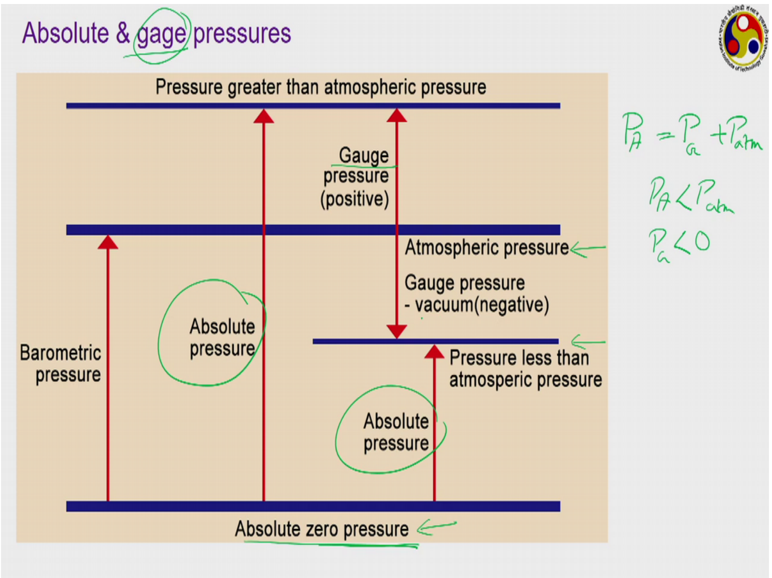

But, now we need to classify pressure into a few categories, before you go for the measurement. Because, we need to be very sure, which pressure we are going to talk about. This is the most common kind of definition or classification of pressure. Generally, whenever you are trying to define the value of pressure, we do that with respect to certain reference length scale. And the most common reference can be the atmosphere itself or I should say the atmospheric pressure. Atmospheric pressure is the most common reference that we generally take.

Now, if this is the point where you want to measure the pressure, then we can do in two ways. One we can define the pressure at this particular point with respect to the atmospheric pressure or with respect to our reference or we can define it with respect to reference, where absolute pressure is where or rather I should say the pressure is really zero or truly zero.

Now, when we are doing this with respect to the atmospheric pressure, then we call that gauge pressure. Here the spelling both, this particular spelling and this particular spelling both are applicable depending upon which language system you are using. I shall be sticking to my definition like this.

However, when you are evaluating the magnitude of pressure with respect to absolute zero pressure, then we call it absolute pressure. So, if P A refers to absolute pressure and P G refers to gauge pressure of the same location, then what will be their relation?

Absolute pressure will be equal to gauge pressure plus the atmospheric pressure. And therefore, once we know the atmospheric pressure value at a particular location, then either gauge pressure or absolute pressure will allow us to calculate the other one.

However, if we are talking about a point which you where the pressure is lower than the atmospheric pressure, then what we should do? They are again like a point here, whose absolute pressure is lower than the atmospheric pressure. Of course, we can define the absolute pressure, because which is we are always defining with respect to the absolute zero and so there will be a positive value of this absolute pressure.

However, if we calculate gauge pressure, then gauge pressure will be negative. Because, here like in the first case our absolute pressure was greater than gauge pressure, because the actual pressure was greater than atmospheric so, gauge pressure was positive or I should say absolute pressure was greater than atmospheric pressure accordingly gauge pressure was positive.

However, when you are doing this particular case, here the absolute pressure here the absolute pressure is less than atmospheric pressure, so the gauge pressure is negative. So, we can define it either by a gauge negative gauge pressure or there is an alternate way of doing this, which is the definition of vacuum pressure. Vacuum pressure refers to vacuum pressure we use this term vacuum pressure we use, only when we are talking about an absolute pressure lower than atmospheric pressure.

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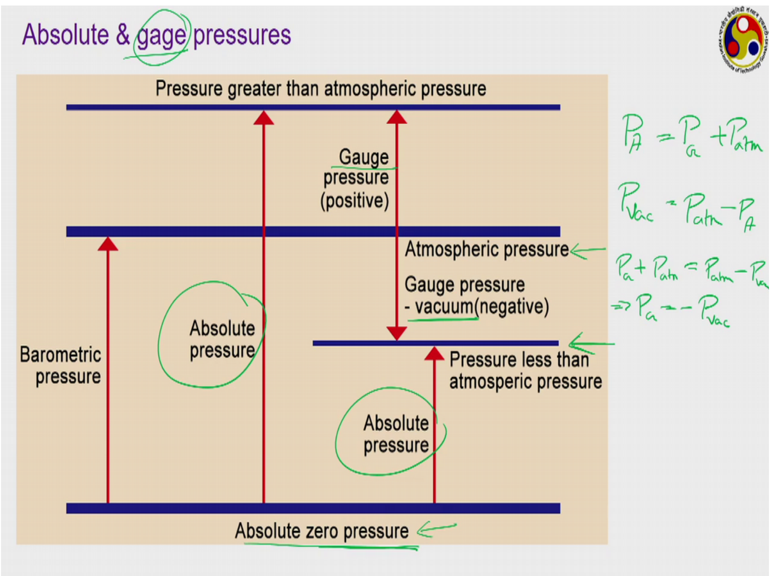

In that case, this vacuum pressure is defined as P atm minus P absolute. It recognizes the fact that the absolute value of pressure is lower than atmospheric pressure, so that we get a positive value of this vacuum pressure. Now, if we compare this with the definition of the gauge pressure, then what we are going to get?

If we compare the this, then from the first definition absolute pressure will be P G plus P atmospheric and from the second definition it will be equal to P atmospheric minus P vacuum, which is gauge pressure is equal to minus of vacuum pressure. Vacuum pressure will be a positive quantity and gauge pressure will be a negative quantity at this particular location, where the absolute pressure is lower than the atmospheric pressure.

So, both gauge and absolute pressures are used you will find pressure measuring devices pressure transducers or pressure gauges, which are coming in both ways, that is some devices which can give you absolute pressure or some devices which can give you the gauge pressure. Quite commonly, you can find gauges, where it is clearly specified, whether it is measuring the gauge pressure or absolute pressure.

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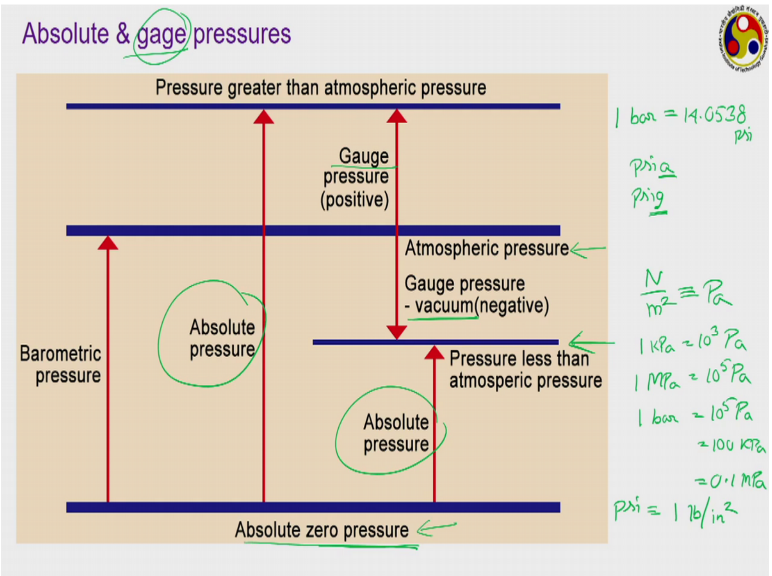

What is the unit of pressure measurement can you say, of course the most common si unit is force per unit area that is Newton per meter square which is called Pascal. But, one Pascal being extremely small quantity, quite often we deal with kilo Pascal which is 10 to the power 3 Pascal or mega Pascal which is 10 to the power 5 Pascal.

But, one unit which is very common in practical use for industrial application that is 1 bar refers to 10 to the power 5 Pascal that is 100 kilo Pascal or 0.1 Mega Pascal. Bar is generally very well used probably the most well used value most used value of or I should say the unit of pressure that we commonly use in engineering.

Now, these are in SI units, but we can also have British units, several pressure measuring devices, you will find where the measurement is given in terms of British unit. And the most common unit is psi; psi refers to pound per square inch that is, it refers to a force of 1 pound weight that is the weight of a body having a mass of 1 pound divided by the area of a one inch square or a square having side of 1 inch.

Now, what is the conversion factor between the two? We can easily put the relation between kg and pound and meter and inch, and you will get that 1 bar is equal to 14.0538 psi. So, this is a very common relation, you will quite often found that in some laboratories maybe at your college or universities or even when you are going to some industry for your professional purpose, you will find the pressure measuring devices are given with unit of psi a or psi g. Do not get confused, their unit actually is psi, but this a or g refers to if it a is there, then it is giving you the absolute pressure. Whereas, if g is there it is giving with the gauge pressure, you have to add the atmospheric pressure to the second case to get the absolute value.

Another very common very I should not say it is commonly used, but another possible unit of pressure that is generally used for very low pressure. Like when you are talking about a point, whose pressure is somewhere, very close to the absolute 0 will below the atmospheric pressure. There if we go for a vacuum pressure or gauge pressure kind of measurement, there may be lots of errors because small, because we have to understand that atmospheric pressure itself is not a constant.

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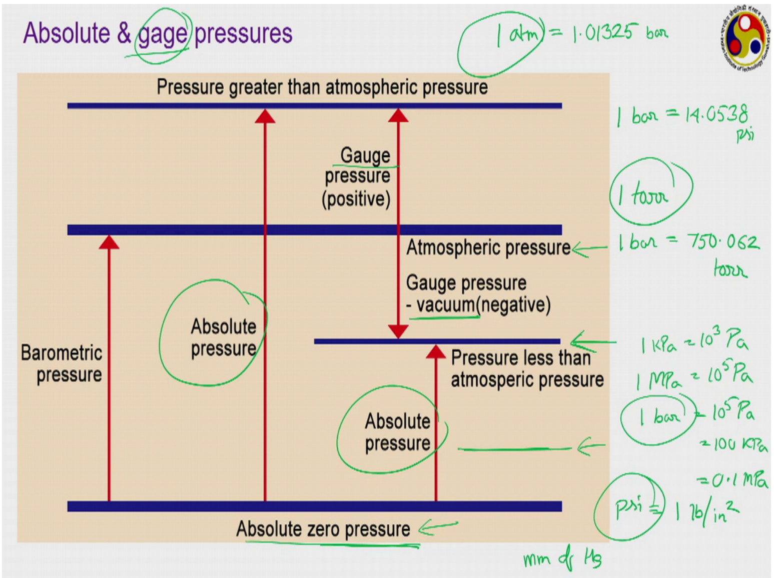

At sea level, the standard atmospheric pressure 1 atm, atm is also commonly used as an unit for pressure is given as 1.01325 bar that is slightly above 1 bar and that is the reason of having bar as such important unit of pressure. Now, one atmospheric pressure is not 1 bar, but slightly greater than this. But, this is that pressure value at sea level, these are normal atmospheric pressure.

But, at different locations on the planet, the value of pressure can keep on changing. Even at the same location also, the value of pressure may fluctuate depending upon the weather condition. And therefore, when you are talking about a such low pressure levels, there is small fluctuation in the atmospheric pressure may lead to significant amount of error in the absolute pressure value at this.

In that case, we sometimes use another unit, which is called 1 torr t o double r, 1 torr is extremely small value. Instead of writing 1 torr, I should write that 1 bar is equal to 750.062 torr. You do not need to remember this particular conversion factor 1 bar is about 750.062 torr. There is another way quite commonly used unit of pressure which is in terms of mercury column, but I shall be coming back to that shortly afterwards.

So, common units of pressure can be either in terms of bar or kilo Pascal or in terms of psi's, sometimes in terms of atmosphere. And if you are talking about very low pressure, we may also have to deal with this torr. And the one which I shall be talking back to talking later on that general is given as millimetre of mercury column which we shall be discussing very shortly. And that can also be related to torr or bar or psi.

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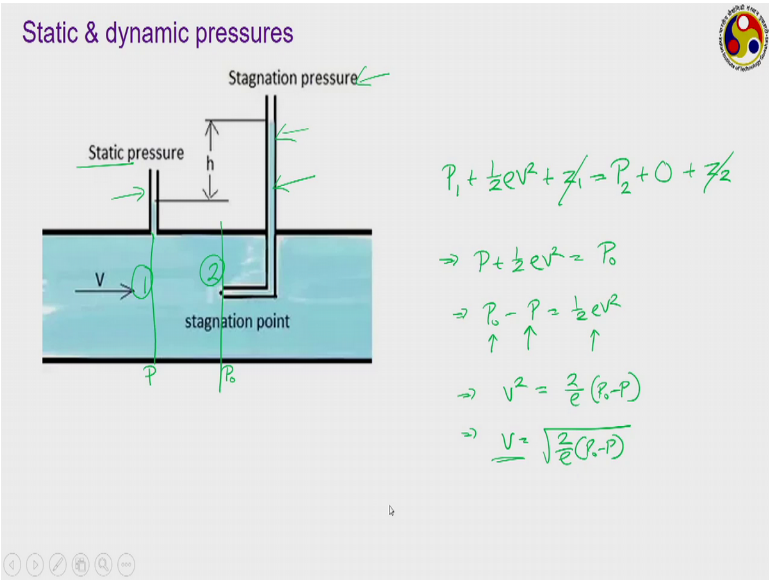

Another classification of pressure that is very important in fluid mechanic measurement is the terms static and dynamic pressure. Now, just consider the picture that is shown here. Here we have a channel through with some liquid is flowing. Actually, I should not say liquid, some fluid is flowing, it can be liquid or can be gaseous, but effect is more pronounced in case of liquids and actually effect can be quite more quite pronounced in case of gases also, when this value V the velocity is high.

Now, if we are measuring pressure at this particular location by using some kind of tapping, which is parallel to the floor or which is normal to the flow direction that this fluid is allowed to flow in its normal course without affecting the fluid velocities, then it will give you a certain pressure value. And this pressure is known as the static pressure.

However, if we mount the pressure measuring device this way then the fluid elements which are flowing in this direction as they come in contact with the tip of this. Then at this particular position to satisfy the no slip boundary condition its velocity has to become 0, because it is in contact with the stationary surface now. And so is velocity will become 0.

Now, as the velocity is becoming 0, then what is happening? It is losing all the kinetic energies and as it is losing the kinetic energy, this entire kinetic energy gets converted to pressure. Thereby, the pressure measurement that we get at this particular point, this measurement will be greater than this particular value. Because, in the second case the kinetic energy also gets converted to pressure and therefore the this kinetic head gets added to the static pressure to give you a higher value of pressure which is known as the stagnation pressure. Stagnation refers to the stagnation of the fluid at this particular point also called the stagnation point.

Now, let us clean up the diagram. Let us say this particular point is 1 and this particular point is 2, here the 2 refers to actually the stagnation point. Now, if we apply Bernoulli's equation at this two particular point or may be one plane through one another plane through this stagnation point, the one let me be a more species and this one refers to the point where we measuring the static pressure.

So, let us say here the pressure is p, here the pressure is p naught. Then if we apply Bernoulli's equation, then at 0.1, we can write P 1 plus half rho v square rho being the density of the fluid plus z 1, z being the elevation of location 1 or this 0.1 with respect to certain datum is equal to P 2, which is equal let me just write P 2 now plus velocity is 0 plus z 2.

Now, if z 1 and z 2 are equal to each other which is frequently the case, we can neglect that. So, P 1 becomes P plus half rho v square is equal to P naught at the stagnation point. So, we are seeing that this P naught is higher than the pressure at point number 1. So, this P is the static pressure, P naught is called the stagnation pressure and this is often called the dynamic pressure that is the kinetic head or the pressure gained because of the conversion of kinetic energy to pressure energy, this is called the dynamic pressure.

In fluid mechanics, we can easily measure both the static pressure and the stagnation pressure. However, dynamic pressure is not that easily we cannot even a dynamic pressure directly, rather we go for both static and stagnation pressure measurement and from there we can calculate the dynamic pressure as their difference.

In fact, this also provides a very easy way of calculating the velocity of the fluid, because what we can easily see that v square will be equal to 2 by rho into P naught minus P or v is equal to 2 by rho into P naught minus P. So, if for a flowing stream, where the density rho elements constant. If we can get a measurement of the static and stagnation pressure, then using this very simple mathematical formula, we can get the value of the velocity of the fluid, which is one of the very important way of fluid velocity measurement using a device called pitot tube, we shall be talking about this later on.

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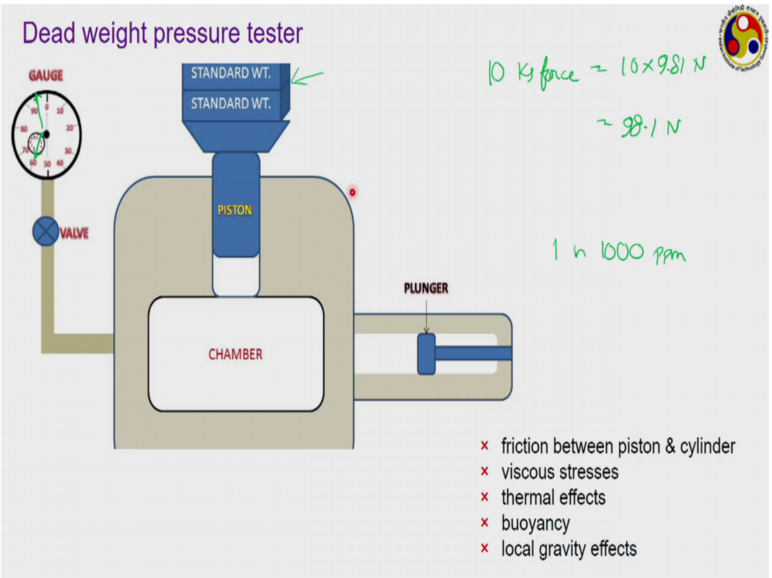

Now, let us come to the once we know this kind of classification that is absolute on gauge pressure and also the static and dynamic pressure, let us talk about a few instruments or pressure measurement. And the first one that we have is deadweight pressure tester, it is a very simple mechanism. However, this is generally used more for calibration of the gauges not for common pressure measurements that is why they are generally available either in the standard laboratories or places which are used for manufacturing of pressure gauges.

Now, here we have a chamber generally filled with certain liquid, certain heavy density fluid. And one side of this chamber is connected to this plunger pump, by controlling this plunger pump by operating this one we can change the pressure inside this chamber. Now, on top of this chamber, we have a piston and we have standard weights or rather on top of the piston, we have a platform, where we can put in some weights. On the other side of the piston, we have the gauge which is connected, and this is the gauge which is going to be calibrated using this test facility.

Now, initially the chamber is filled with certain fluid and it is initially at some pressure, we can control the pressure of this into is one by contrary operating the plunger pump, and also by changing the weight on top of the piston. So, what we do, initially put certain kind of force or standard weights on the piston. So, let us say we want to get a measurement of 10 kg force; that is 10 kg force refers to 10 into 9.81 Newton that is 98.1 Newton.

So, what we shall be doing, we shall be taking standard weight of 10 kg, and that will be put on top of the piston. So, the initial pressure may be quite high compared to the initial weight of this the weight put by this piston may be quite high now, for the fluid inside the chamber, so we start the plunger pump.

And we keep on operating the plunger pump, thereby increasing the fluid pressure by adding more and more mass of fluid inside the chamber. Till the moment this piston and weight assembly starts to float. It starts to float means, now it has reached some kind of pressure balance that is the pressure of fluid inside this is just sufficient to balance the weight of this standard weight. Then whatever value whatever reading the gauge is showing that should be equal to this 98.1 Newton that is the gauge may be pointing to a location somewhere here. So, we can put the mark of 98.1 Newton.

Now, we can change the weight on top of the piston and thereby is setting up a new value, and accordingly modify this. Like suppose in next case, we have set up force of 60 Newton. So, once the system becomes stable, then wherever the pointer is pointing that has to be 60 Newton. This so we can keep on calibrating or pressure gauges and also we can recalibrate any existing instrument.

This is a very standard assembly and we can by precise control of the plunger pump and the weight, and also this gauge calibration procedure. We can get extremely accurate measurement something in the range of maybe 1 in 1000 ppm that is in every 1000 parts, there may be error of just one part, this level of accuracy you can easily reach this.

However, there are a few concerns that our considerations that we have to be mindful of. Like the friction which may be acting between the piston and cylinder. As the piston starts to float or it starts to move because of the increase in the pressure inside the chamber, some energy may be lost because of the friction. There will be viscous stresses of course, because we are talking about the fluid which starts to move inside the chamber because of the action of the plunger form. And viscous stresses may get developed significant, viscous stresses make a develop inside the chamber.

There can be thermal effects because of the operation of the pump energy gets added to the fluid inside the chamber itself. And that may change the density of the fluid, and also other associated properties. Buoyancy is another factor, as you are interested to get the piston floating into the fluid. Buoyancy is definitely an important factor.

Local gravity also may keep on varying, so where you are looking doing this experiment that also matters. Therefore, for every different location and for every scenario, it is important to calibrate the tester itself, before we can start calibrating pressure gorgeous. So, they do it pressure tester is more for calibration purpose, but similarly balance of; balancing the weight of some external thing to get the value of pressure is used in another very common kind of device, where instead of using solid, we keep on using fluid or to be more specific, we can keep on using liquid columns and something which falls under this manometry.

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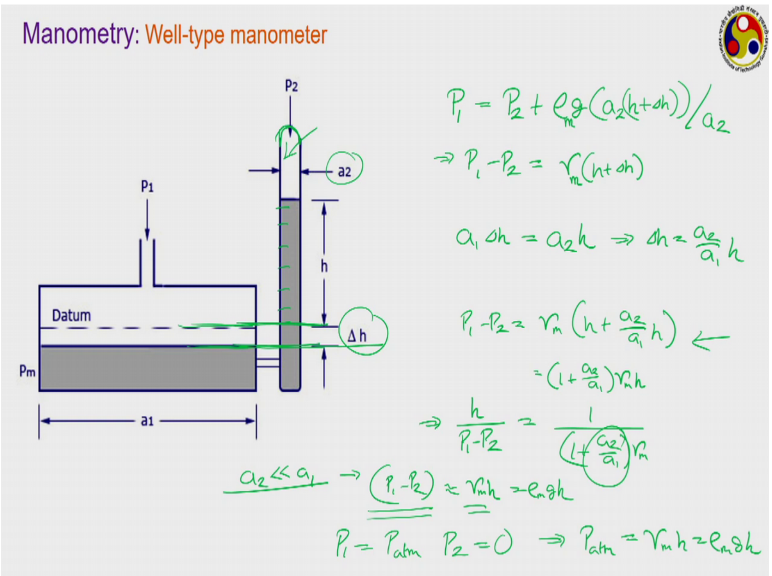

You definitely have heard about data manometers and that is what we are going to talk about here. In manometers, we have a liquid column to balance the force. Just look at this, this is the; they are generally two broad kinds of manometers. This is the first one which is called the well-type manometer, the other one is a u-tube manometer.

In well-type manometer, we have one big chamber or shell and connected with a small diameter tube. So, both are connected this is the connection here, so that fluid can keep on moving in and out of the tank and also the cylinder. Let us say the tank is having a diameter of a 1 sorry, the cross section area of a 1, and the cylinder is having a cross-section area of a 2. This datum is the initial level of fluid in both tank and the cylinder, when both are at equal pressure.

Now, we have imposed a pressure P 1 on the tank and a pressure P 2 on the cylinder. Because of that, if P 2 is lower than P 1, then there will be a reduction in the fluid level on tank 1 or on the big tank. Thereby displacing some fluid from the big tank into the cylinder and leading to the formation of in water column or I should not say water its fluid column, generally liquid column.

So, if we now write a pressure balance, pressure balance we can write with respect which point? Let us say this is the level that we pick up to write a pressure balance equation. So, what is the pressure that is acting on the tank side, the pressure will be equal to P 1 itself.

Similarly, what is the pressure that is acting on the cylinder side, cylinder side pressure will be P 2 plus the pressure corresponding to the weight of this liquid column. Now, how much is the weight of the liquid column? Weight of the liquid column will be let us say rho is the density of this liquid into g is the gravity into volume of this liquid column will be a 2 into h plus delta h, this is the volume of the liquid column, this divided by the cross section a of the tube, this is the pressure or we can write P 1 minus P 2 is equal to is gamma into h plus delta h, where gamma is rho into g. Quite commonly, we use a subscript m to denote, this is the density of the fluid inside the manometer or the manometric fluid, similarly gamma m is the rho m into g product.

Now, this delta h can be related to this area is a 1 and a 2 how, how much is the displacement of fluid or change in volume of fluid in tank 1? This is the initial fluid level, this is the final fluid level in tank. There is a difference of height delta h and we also know the cross section area. So, the change in fluid volume in tank 1 or reduction in fluid volume is just a 1 into delta h and that fluid where it has gone. This is we are talking about a liquid which is incompressible, so the volume has to be conserved.

And if we assume the volume to be conserved then whatever is the reduction in the volume in tank that has to be the gain in volume in the cylinder. Now, how much is the change in volume, the cross section it is a 2 and there is a change of height h, you have to mindful that this was the initial level, this is the final level. So, from there we can say that delta h is equal to a 2 upon a 1 into h.

If we take it back to the previous equation P 1 minus P 2 is equal to gamma n into h plus a 2 upon a 1 into h or 1 plus 2 upon a 1 into gamma m into h. So, by choosing this ratio a 2 by a 1 at the design level itself and also the density value gamma m or I should say the density value rho m or the value of gamma m. We can relate even significantly large pressure levels P 1 2 in terms of h, what; how we can define a sensitivity of this instrument. Do you remember how we defined sensitivity in the very first week of this? Sensitivity refers to the change in output with respect to the change in input.

Now, what is a output here, your output is this change in the liquid column height h. And how much is your input that is the pressure difference P 1 minus P 2, so how much is that that is equal to 1 by 1 plus 2 by a 1 into gamma m. So, this is the sensitivity of the instrument. If this a 2 is extremely small compared to a 1 that is a 2 is negligibly small compared to a 1, in that case P 1 minus P 2 is equal to or I should say is nearly equal to gamma m into h that is manometric fluid density into g into h.

So, assuming the fluid density to remain constant and gravity you can this g gravitational acceleration can also be assumed to be constant. Then we are having P 1 minus P 2 to be a linear function of h and therefore on this particular cylinder surface, we can also put proper scale or length scale which can be directly calibrated in terms of the pressure difference this.

So, this well-type manometer is the first kind of manometer a very simple instrument, but we can get quite accurate measurement, if we just by knowing the value of this gamma m and also this ratio of a 2 upon a 1, which general is provided by the manufacturer itself. So, well-type manometer, however there is one problem this kind of things or actually any manometer, they are not that much suitable for dynamic pressure measurement. As long as we are look, because they need sufficient some amount of time for this liquid column to get developed and get settled at a particular elevation.

And therefore, if you are looking for too frequent change in the value or pressure, w we may not be able to capture the corresponding value of h properly. That is why, manometers are excellent devices as long as we are looking for static pressure measurement and also we have to be careful of the range of pressure, they are generally not suitable for very large value of this P 1 minus P 2, whatever may be the choice for rho m or the ratio a 2 by a 1.

As long as we are working with low to moderate pressure difference levels or pressure levels and there is there is more or less static or steady state condition manometers are very good devices for pressure measurement. However, if you are looking for either measurement of very large pressure or also very very small pressure difference between this P 1 and P 2 or also if you are looking for very frequent changes in pressure, we may have to look for different devices.

But, now think about the situation, where your P 1 is equal to the atmospheric pressure and P 2 is equal to 0. How can you have P 2 equal to 0, let us just close the top of this cylinder. And the area that is this area on top of the liquid column, let us evacuate this using some vacuum pump or etcetera. Then what will be your relation going back to this particular equation, your P atmospheric will be equal to 1 plus a 2 upon a 1 into gamma m into h or if a 2 is extremely small compared to a 1, then this just becomes gamma m into h that is rho m into g into h, so we can get a measurement of the atmospheric pressure. And that is what we do in case of a barometer, which is just a modification of this well-type manometer.

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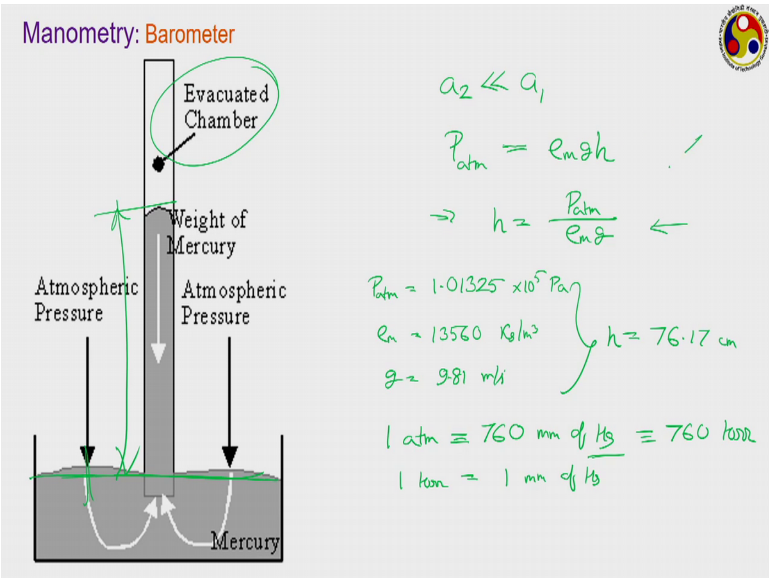

Here we have just one liquid pool which is open to atmosphere, and a small diameter liquid column cylinder, which is generally a capillary tube. And as the atmospheric pressure app gets applied on this, if we take a pressure balance at this particular location, then the atmospheric pressure which is acting at this particular point has to be balanced by this particular liquid column.

This particular liquid column or weight of this liquid column must balance the atmospheric pressure, which is acting on the free surface of the liquid pool, commonly mercury is the choice as a liquid. And accordingly, here if we compare the ideas generally a 2 is refers to a capillary tube, which is having an extremely small diameter, a 2 really is extremely small compared to a 1. And we comfortably can equate this one to be equal to rho m g into h, h being the column of this mercury inside this.

Mind you we can have liquids of any density or any kind of liquid in the column, but one advantage we get is this h is equal to m into g that is h is inversely proportional to this manometric fluid density. Therefore, if we are using a fluid having low density is something like water, water is not very low density, but compared to mercury it is extremely small, then this value of h will be much much larger. Density of mercury is quite high 13.6 times more than water under normal atmospheric condition. And therefore, corresponding value of h is also 13 to 14 times lesser compared to what we would have got with water itself.

Now, barometers are very standard devices used every year in the world and for ages, and also this simple relation gives us another way of defining a pressure scale, which we I have mentioned if you slice back. Now, standard atmospheric pressure is of mentioned P atm is equal to 1.01325 bar or maybe if we write in terms of Pascal's, so this into 10 to the power 5 Pascal, rho m for mercury is 13560 kg per meter cube, small g can be taken as 9.81 meter per second square.

So, if we combine this value, your h comes something like 76.17 centimetre, that is under standard atmospheric condition, the height of this mercury column will be about 76 centimetre. And that provides another scale for pressure, where we can easily relate one atmospheric pressure to this height of what are called height of mercury column or as a matter of fact a column of any liquid.

So, quite frequently, we take as a normal conversion, we take 1 atmosphere as 76 centimetre or 760 millimetre of mercury. And as I mentioned earlier about torr, 1 torr is actually 1 millimetre of mercury, therefore this is equal to 760 torr. So, liquid column height can also be a quite frequently used, what pressure unit which we can instead of mercury, we can use any other fluids also and easily get a conversion.

Now, well-type manometer is one of them, but before I move on to the next one, one we have to be careful that in this evacuated portion perfect evacuation is never possible in practice. So, some amount of mercury vapour may remain there. However, under normal atmospheric condition or I should say normal temperatures like 20 to 30 degree Celsius, which is the normal atmospheric temperature. The vapour pressure of marker is extremely small negligibly small, so we can easily carry on with this relation.

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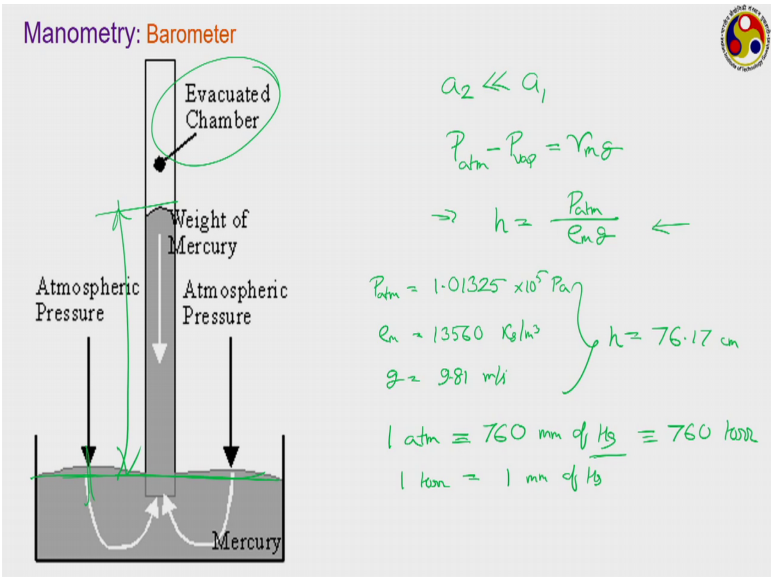

However, if we are talking about significant value of this vapour pressure, then this relation is to be modified. In that case, we have to write this one as P atm minus P the vapour pressure of mercury or whatever fluid you are using in that so called evacuated portion should be equal to gamma m into g and this should be the correct relation. So that correction if you are looking for extremely highly or extremely accurate value of this atmospheric pressure, then this vapour pressure correction must be considered.

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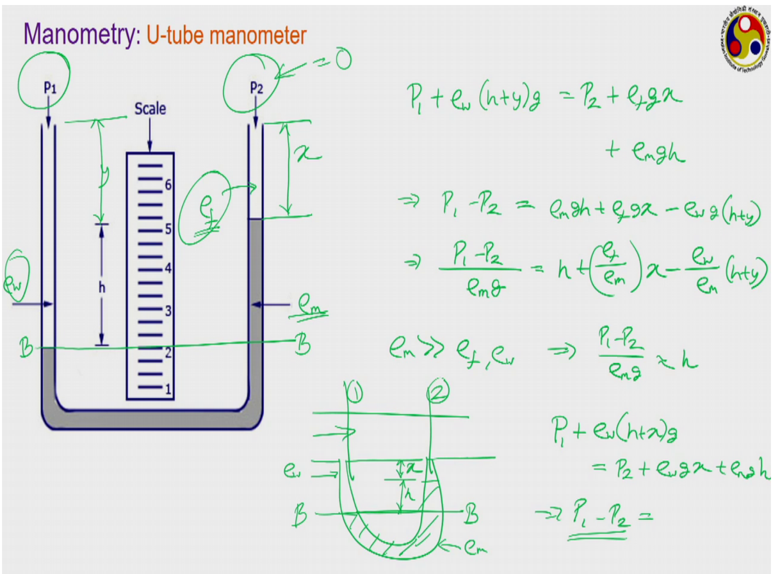

So, the next kind of manometer that we get the other variation, where we do not have a liquid pool rather we just have one tube, which is bend in the form of an U. One side of the tube or rather both the arms can be connected to different locations, we can also keep one connected to the location or you want to measure the pressure, other key being open to the atmosphere.

Accordingly, we get some kind of difference in the fluid column level, and the difference can directly be related in terms of a scale like shown in diagram. The scale can be calibrated like this height h can be directly calibrated in terms of any unit of pressure bar or psi or mercury column, whatever you want and accordingly, we can get a pressure measurement.

So, if we take say this is the level, along which we want to measure get a force balance. Let us say rho w is the density of the working fluid, which is connected to this pressure P 1. And rho m is the density of the mercury manometric fluid m may not be necessarily mercury, it can be any other manometric fluid also. And then on top of this from this particular elevation to this particular position, let us say this distance is y, and this to this distance is x. We can have some other fluid connected to this portion also. Let us say this fluid is having a density of rho f.

Then if we take a pressure or balance or force balance at this cross-section B B, then at the left hand side we have P 1 plus rho w into h plus y into g is equal to P 2 plus rho f g into x plus rho m into h into or g into h or P 1 minus P 2 is equal to rho m g h plus rho f g x minus rho w into h plus y into g or let me be consistent g into h plus y.

And quite often, we would like to represent this one as divided by rho m into g, so that we can convert this one to some kind of length scale. Then it just becomes h plus rho f by rho m into x minus rho w by rho m into h plus y. In most of the practical cases, this P 2 remains to be the atmospheric pressure, and rho f become density of air. And in most situations particularly, if you are going for a mercury kind of fluid, you may have rho m to be significantly larger than both rho f and rho w, in that case P 1 minus P 2 upon rho m into g will nearly be equal to just h. So, just the measurement of h itself is going to give you the value of the pressure that you are looking for.

However, if the value of rho w or rho f is significant, then we have to consider them given the calculation itself, which is not a very difficult one. Once we know all this density values, you can easily calculate the value of the pressure difference between P 1 and P 2 or another important thing is that this one particularly, when this P 2 is atmospheric pressure, you can really get a measurement of the gauge pressure using this manometer. Because P 1 minus P 2 is the one that you are evaluating which is precisely the idea of gauge pressure means what you are getting is P 1 minus P atmosphere that is P 1 gauge or P gauge pressure at location one.

So, U-tube manometer can easily be used for calculation of gauge pressure. However, if we are looking for an absolute pressure measurement, then P 2 should be equal to 0, if we want absolute pressure measurement. Quite often, we use this kind of manometer for differential reading as well. Like think about we have a flow stream through this some fluid is flowing in one location to other. And we want to get the pressure difference between these two locations. So, this is our location 1, this is our location 2. Then we can easily connect a manometer between these two locations.

And accordingly, get a reading like it may be possible that, this is the manometric fluid which is showing and elevation difference of h and on top of the fluid, we have this x, it is left to it. Now, if we across this particular section say B B, if we take a force balance again, rho m is the density of the manometric fluid and rho w is the density of the working fluid.

Then on the left hand side, you will be having very similar way P 1 plus rho w into h plus x into g. And on the right hand side, you will be having P 2 plus rho w g into x plus rho m g into h from there you can get P 1 minus P 2 which is the difference in pressure between location 1 and 2. This kind of manometers are called differential U- tube manometer, so just differential pressure manometers. U-tube manometer can different kinds of variations. If we here also the same way we can calculate an expression for sensitivity, but that will be quite similar to what we got in case of well-types.

Now, if we are looking for extremely small pressure difference measurement that is this P 1 minus P 2, then or if our manometric fluid is having a density lower than the working fluid density, then how we can do it? You can see that the situations that we are talking about here, always the manometric fluid density that is this rho m has to be greater than this rho w or rho f. However, if rho m is lesser than this rho w or rho f, then definitely we cannot use this, because in that case the working fluid will come down and push this manometric fluid in the upward direction.

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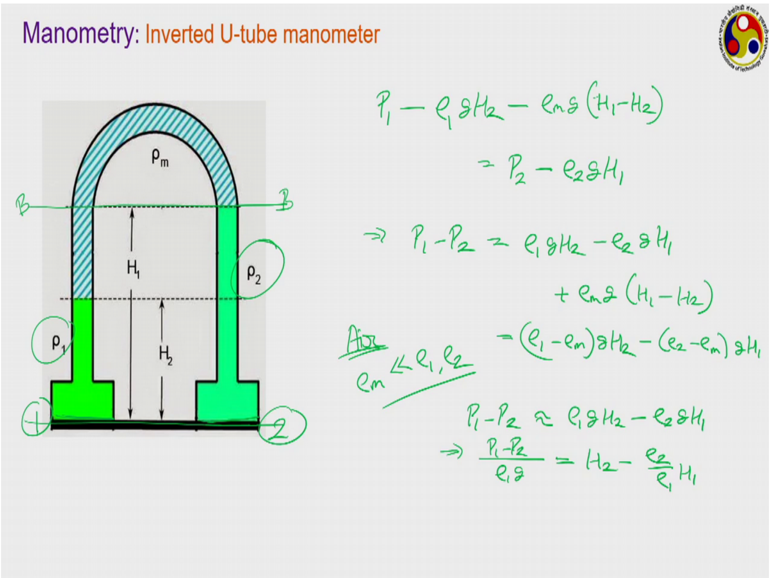

And in that situation, therefore what we do is just to invert the manometer in a configuration like this, this is called an inverted U-tube manometer. In case of a inverted U-tube manometer, let us say this is your location, where you want to measure the pressure, this is your location 1, this is your location 2.

And here the manometric fluid is having density lower than the densities of rho 1 and rho 2. So, if we again take a pressure difference or pressure balance between location 1 and 2, then what we are going to get at point; if we take say a pressure balance at this particular location B B. Then, what will be your pressure on the left hand side? Your pressure will be P 1, P 1 is the pressure at this particular point minus there is a column of height h 2 of liquid rho 2, so rho 2 g into H 2 minus if there is a column of height h 1 minus h 2 of manometric fluid, so rho m into g into H 1 minus H 2.

What about the right hand side P 2 is the pressure, at this particular location minus there is a column of height H 1 of density liquid density rho 2 g into H 1. So, P 1 minus P 2 will be equal to in the first case it should have been rho 1 sorry, so it should be rho 1 g H 2 minus rho 2 g H 1 plus rho m g H 1 minus H 2. And we can separate it out in two components that is if we take say the H 2 part out, then we shall be having rho 1 minus rho m into g into H 2 minus rho 2 minus rho m 2 g into H 1.

And now depending upon the value of rho 1, rho 2, and rho m, we can easily calculate the pressure difference between these two location. Despite the density of the manometric fluid being lower than the density of both the involved fluid. Quite often in inverted u U-tube manometers actually use air as the manometric fluid.

And if you are using air as the manometric fluid, then this rho m is negligibly small compared to both rho 1 and rho 2 in most of the practical cases. In that case, your P 1 minus P 2 will be what? It will be just rho 1 g H 2 minus rho 2 g H 1 and you can go for the subsequent calculation of the density or I should say the pressure difference in terms of whatever fluid you can go for. Like if rho 1 is the fluid that you want to scale the pressure difference, then you can write this as P 1 minus P 2 by rho 1 into g is equal to H 2 minus rho 2 by rho 1 into H 1.

So, inverted U-tube manometer is just a variation or inversion of the conventional U-tube manometer and then we can use very light manometric fluid or at least manometric fluids having density lower than the working fluid density. Now, there are two ways, we can increase the sensitivity of this manometers because, we know that the sensitivity in manometer is always given in terms of the change in elevation or elevation of the liquid column divided by the pressure difference. And so if we want to increase the sensitivity, somehow we have to increase the elevation of the liquid column. One way of doing this is to change the manometric fluid density, but that may not always be most practicable one.

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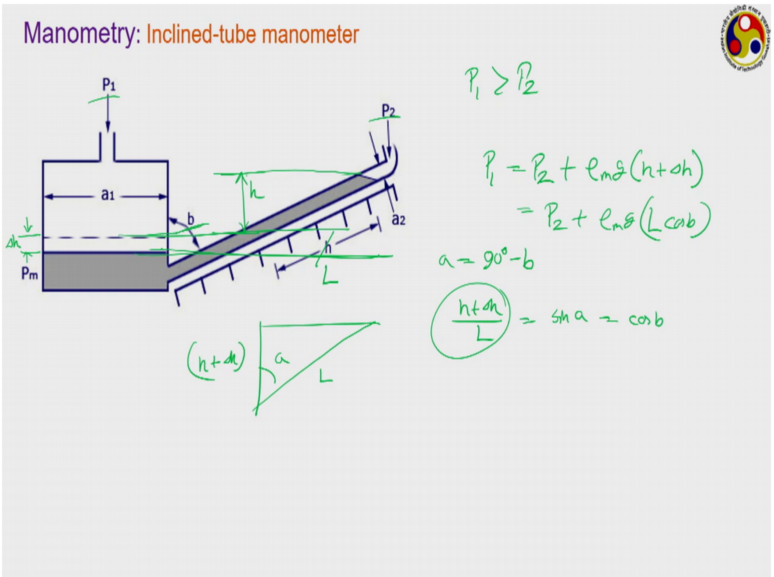

And therefore, we can go by just modifying the design itself. We can change the sensitivity of the instrument or rather increase the sensitivity of the instrument. So, I shall be quickly discussing about two of the methods. One is to use the inclined tube manometer, it is the well-type configuration or quite similar to the well-type configuration.

You can see here the instead of having a vertical tube, we have inclined the tube to some angle, this angle is b. Now, this is supposed to the initial datum level, this is the initial datum in both well and inclined tube the fluid was at this particular level. Now, because pressures P 1 and P 2 have been imposed on this which are different to each other. P 1 greater than P 2, then there is a reduction in the water level or what I sorry, not water fluid elevation in the well. So, this is the reduction in the elevation level of fluid which let us say is delta h, corresponding to this there is an increase in the elevation of the fluid.

So, let us say this is at the datum, this is the final position. And so there is a change of h elevation h between the two. Then how much is the total net difference in this, so net difference if we sorry, if we take this as our working section and if we take a pressure balance, then the same way we can write that on the left hand side your pressure is just P 1, on the right hand side your pressure is P 2 plus how much is the height of this. Height of this column is rho m g into height is h plus delta h.

However, this h plus delta h, actually in this diagram this h is shown as the this let us say, let us call this l, where l refers to the length of this column along the tube or in the inclined way. Now, h plus delta h is the total elevation difference between the fluid level. However, l is the length along the inclined tube from this location up to the tip of this. So, what is their relation. So, we are getting a triangle something like this. If we draw the triangle properly, then this is what we are getting, this one is our L, this one is h plus delta h.

And what is the intruder angle, the intruder angle between them, this particular angle is given as b. So, this particular angle, let us say this angle is a, and a is 90 degree minus b. so, what is the relation between them? So, h plus delta h divided by L is equal to sine of a that is cos of b. So, if I put it back here, so it will be equal to P 2 plus rho m g into L of cos b.

And by changing the value of b, therefore we can keep on changing the value of L or this particular ratio itself. Definitely the value of L will be much larger compared to the value of h plus delta h. And it will be much easier for us to identify the length of the liquid column in the inclined tube. Even for much smaller value of pressure difference between P 1 and P 2, we can easily calculate this.

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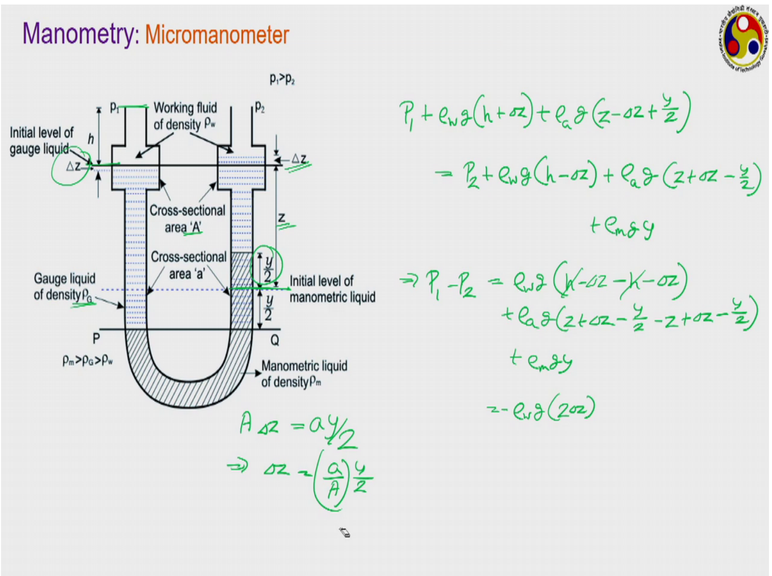

The other way of increasing the sensitivity is the use of micro manometer. In case of micro manometer, we are still using an U-tube manometer, but here both the ages or lengths of the tubes are connected to one large dimension tanks or some kind of bulbs. And here all we are using a second fluid, which is also known as the gauge fluid.

Now, see here carefully here we have three fluids. We have a manometric fluid rho m, which is this shown by this hatched is the manometric fluid. Then we have a gauge fluid, which is shown by these dots, which is having a density rho g. And now we have the working fluid, which is just by the white space.

Initially, this was the level of the fluid, this was the initial level. This is the initial level of the gauge fluid in both the tanks on top of that we have the working fluid having density rho w. And this was the initial level of the manometric fluid. Now, as soon as we are putting a pressure difference P 1 and P 2 between the tank or P 1 minus P 2, then there is a delta z amount of reduction in the gauge fluid elevation on the left hand side.

Correspondingly, both these tanks are actually having same cross section area; so, a cross section area of capital A. Now, because areas are same, so there will be the same amount of change in the elevation or increase in the elevation of gauge liquid level in the other thing, other height or other bulb, but because of that there is a as the delta z amount elevation difference is happening in the bulb, there is a much larger change in the height of this gauge liquid column in this which is given by this y by 2. Correspondingly, there is y by 2 amount of increase in the elevation, on the other side of the manometric fluid.

So now along this cross section P, Q if we take a pressure balance, then what we are going to get, on the left-hand side, we have first P 1 which is the pressure which is acting here. Then we have the working fluid, working fluid of density rho w, so we have rho w g into how much is the height of this, height is h plus delta z. So, h plus delta z is the height of the working fluid, then we have the gauge fluid. So, how much is the height for the gauge fluid, it is rho g into g into how much is the height, it is height is if you see z is the height from the initial; between the two initial levels, initial level of the manometric fluid and initial level of the gauge fluid.

So, let us put z, there is a reduction in this so, there is a minus delta z minus y by 2 sorry, there is a plus y by 2. So this much is the total height see from this point to this point, it is z minus this small delta z. And now this is your y by 2, so rho g into z into this particular elevation is on the left hand side.

Now, what about the right-hand side, on the right-hand side we have P 2 plus a column of the working fluid rho w g into how much is the height of the working fluid, there is an increase in the height of the gauge fluid by off amount delta z, so that much reduction has taken place on the working fluid side, so that is h minus delta z. Then we have the column for this gauge fluid, it is rho g into g into how much is the height for this gauge fluid, it is z plus delta z minus y by 2 plus we have the manometric fluid rho m into g into how much is the manometric fluid, it is just y.

Now, as all the fluids are compressive incompressible in nature, so there is a delta z amount of reduction in the gauge fluid hide in the bulk. So, change in volume is capital A into delta z, capital A being this area. And then corresponding increase of elevation in the other arm on the left hand side, how much is that small a is the cross section area into y, this much is the change that has taken place or I should not say y actually these are the initial level, so y by 2 is the change that has taken place.

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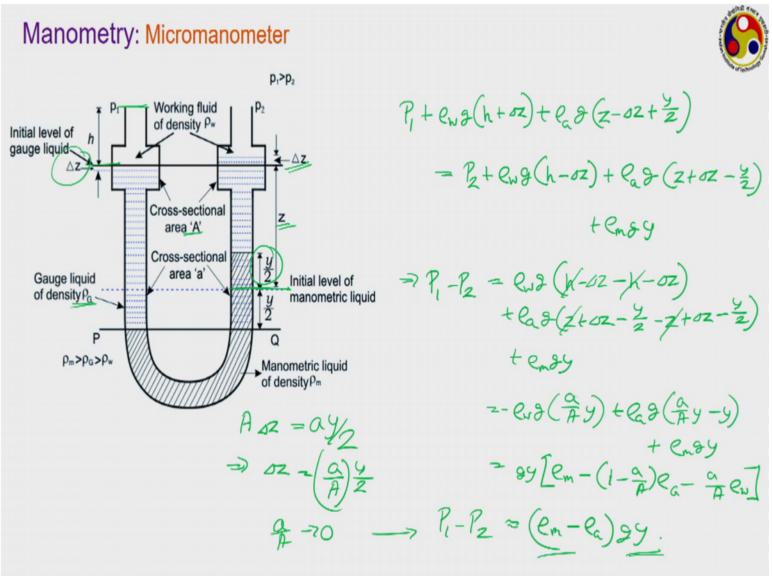

So, delta z is small a by capital A into y by 2, we can take it back here. So, P 1 minus P 2 is equal to rho w g into h minus delta z minus h minus delta z, so that corresponds to rho w plus the gauge fluid. We saw on the left hand side and we are taking from the on the right hand side we had this, this is coming plus rho m g y, so delta z goes off that is rho w g into for this was I should not have struck this out h minus delta z minus h minus little actually h goes off so 2 delta z remains.

And this 2 delta z can be converted in terms of areas as small a by capital A into y plus for the gauge fluid rho g into z. So, here z goes off, but 2 delta z is there which again becomes small a by capital A into y minus y plus rho m g into y.

And if we now take this g into y as common, which is generally done, what we have, we have rho m on one side plus how much coming from rho g. So, small a by capital A being smaller, we can write this as 1 minus small a by capital A into rho g plus or it is also negative, so small a by capital A into rho w. So, we have the expression for this pressure.

And when this small a by capital A tends to 0, then we have P 1 minus P 2 is equal to rho m g y ok, sorry this nearly equals to rho m minus rho g into g into y. When this area of the cross section area of this capillary is extremely small compared to that of the bulb and now, if the difference between the manometric fluid density and gauge fluid density is smaller then why you also keep on increasing in proportion.

Therefore, by suitable choice or suitably combining this manometric liquid and gauge liquid, we can get much higher sensitivity using this micro manometer, and therefore we can easily use this for very very small delta p measurement as well. So, this is the way, we can increase the sensitivity of manometer. And overall there are several types of manometers that we have discussed. In the next lecture, we shall be solving a few numerical examples to see the application of these concepts in practical fluid pressure measurement, but so far I would like to complete today's work here.

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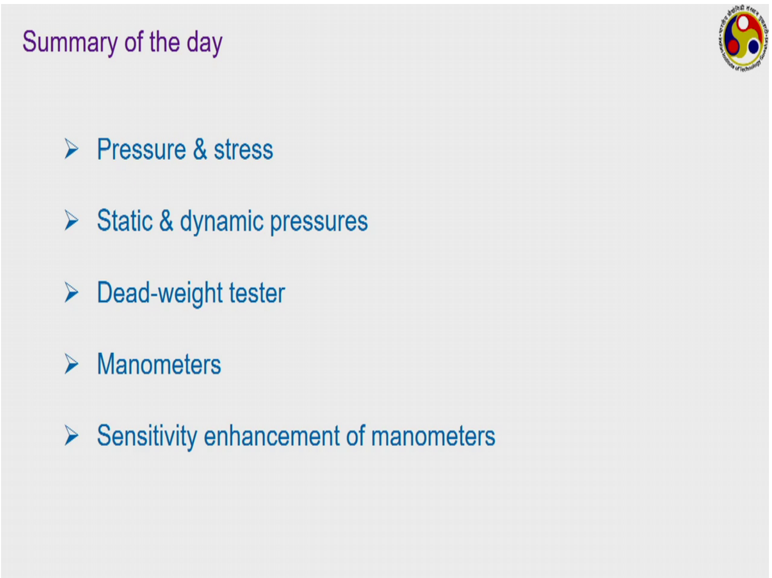

If we just take a quick recap, we have started with the difference between pressure and stress then we talked about the concepts of static and dynamic pressures, absolute on gauge pressures. Then we first talked about the dead-weight tester, which is generally used for calibration of pressure gauges. Then we talked about manometers generally two broad level of classification well-type and U-tube manometers.

And we have also discussed about the barometers as a variation of the well-type 1 and the inverted tube manometer which is actually an inversion of the U-tube manometers. And then we discussed about the sensitivity announcement of manometer two different mechanisms. One that is inclined tube manometer, which is generally more relevant to well-types. And other is the micro manometer, which is more relevant to the U-tube ones. So, just go through these lessons, before we start the next lecture. And therefore, I would like to sign up from here for today.

Thank you very much till the next lecture.