# Cryogenic Hydrogen Technology

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**Week - 07**
**Lecture 35**
**Flow Rate /Fluid Quality Measurement**

You are welcome to this lecture on Cryogenic Hydrogen Technology. We were talking about the cryogenic hydrogen storage and in that connection, we have talked about the different components of hydrogen storage. Particularly we have talked about a double walled vessel, then we have talked about the insulation that is to be used particularly the multi-layer insulation. Then we have also talked about the liquid level that we should have or use in a level measurement. Now, in continuation to that we will also talk about the measurement of liquid flow and of course, it would be in I mean both liquid flow rate measurement. As well as we will find that in two phase flow because this is a cryogenic liquid often you are when you are putting it in a pipe flow or etcetera you will find that it is in two phase condition.

So, we need to find out how much is the ah vapor fraction in it or the, what mass fraction of the liquid that is there in the vapor condition. So, we will try to ah determine this fluid quality ah that is what we call it and then before that we will try to first look at look into it when it is in the ah single ah phase and that too in the liquid phase. So, the topic is of course, the hydrogen storage in cryogenic condition and ah the keywords are like flow rate measurements as I as I have explained you and of course, the quality measurement that is also I explained you ok. So, let us now look into the flow rate measurement ah there are ah numerous numbers of flow rate measurement.

Particularly, if it is in the gaseous condition you will find there are so many ah types of mass flow rate measurement and there are thermal mass flow meter, there are insertion type thermal I mean mass flow meter so many would be there. But ah I mean if it is in the liquid condition then we will find that there are not ah I mean this thermal type of mass flow meter is not often used, but we go for this orifice flow meter ah then we have the venturi ah flow meter then turbine flow meter and coriolis flow meter. So, this is the first 3 type orifice flow meter or venturi or turbine flow meter are ah quite common in cryogenics, but we will ah specifically talk about the fourth one that is called the coriolis flow meter ah because of it is uniqueness ah in all other this flow meters you will find that we are ah as compared to the other one here you will find that the we are directly we are able to measure the mass flow rate. In other probably you will find that you are first you know measuring the volumetric flow rate and then from there you are multiplying it with the density to find out the ah what is called ah the mass flow rate. But in contrast to that this coriolis flow meter will directly give you the flow rate and also we will see other advantages it is having.

So, let us look at the advantages or it is in a possible to directly measure the mass flow rate with the help of this coriolis flow meter and it is it is calibration depends on the geometrical property that we will see just after sometime ah it depends on for a particular geometry if we are able to calibrate it ah and that calibration constant is valid for any liquid. So, if once it is calibrated for a particular liquid you will be able to ah use it for other fluid ah streams ok and it depends on the measurement of ah you know coriolis force which is given by 2 times m into V cross omega. So, this is what is that ah coriolis force ah that will cause difference in the movement of the fluid or you know in the geometrical ah configuration of the ah I mean the thing the ah geometrical construction that we are going to use we will see ah in in the following slides. So, let us try to see if we have a pipe and before that we will just you know summarize the advantages and it is applications ah there are as I said that the direct mass flow rate measurement is possible and also, we can directly measure the density of the liquid. So, there is wide range of in a wide range of flow rate you know we can ah measure the flow rate of this liquid and we have that comparatively very small power requirement.

This power requirement how it is coming we will tell you later and depending on I mean ah about it is application we have the I mean ah so many applications other than cryogenics we have the chemical petrochemical industries, pharmaceutical and food and beverage ah and pulp and pepper industries we have application for this ah kind of coriolis flow meter. Now, let us move forward to the ah I mean a particular type there are various geometries those are possible ah you know where we will find this coriolis effect, but ah we will talk about a simple geometry that is a like a pipe ah. So, this is ah without any flow we will find that ah this flow rate if there is no flow simple ah tube is there and we have 2 sensors ah sensor 1 and sensor 2 and there is some kind of excitation. So, which ah you know ah will give us very small you know ah oscillation we will try to put in and it will be and the oscillation frequency we will try to ah you know keep it very near to it’s what is called the resonant frequency. So, that we do not need a large force ok.

So, we will allow it to ah you know ah vibrate. So, this excitation ah will be done with the help of ah and you know what is called an excitation voltage would be applied and we will measure ah the 2 sensors will be located here to measure the ah it is a displacement. So, it would be as I we have said that it would be like this. So, it will be vibrating and it is you can say with a small amplitude it is vibrating and it is systematic ah I mean ah there is no asymmetry in the oscillation. So, now let us move ah when we are putting a fluid you know we allow ah a fluid to pass through this tube you will find that there is ah earlier it was just moving up and down.

Now, we will find that there is you know a change in the oscillation and ah you know this ah it is ah at some point this sensor 1 will be in ah picking up and the other time you know sensor 2 will have the maximum. So, there is a kind of phase difference that has been created when there is a fluid flow. So, ah this particular ah phenomena is utilized ah we will not of course, describe the detail ah analysis in this at this moment, but what we find is that when there is no flow we are putting an you know ah we are exciting this tube with a particular ah force and we are measuring the ah output with the help of 2 ah basically ah 2 sensors. So, the inflow is ah is like this which will be picked up by the 2 sensors and you will find that the outflow ah which is ah given by this ah sensor 2 you will find that they are in phase ah inflow and the outflow are in quite in phase, but the moment we put them ah what is ah you know that there is a flow ah passing through this as we have seen that this is you know ah are asymmetric and now this inflow and outflow ah are not in phase there is a phase difference and it can be ah related to this phase difference or the phase lag ah it can be correlated with the mass flow rate. So, ah this mass flow rate will be like ah there would be a constant c prime and this is the time lag we have talked about and this is what is that mass flow rate.

So, once ah for this kind of straight tube as we have said that we have a straight tube we are exciting it with a particular frequency and that frequency is very close to it is a resonant frequency, but it is oscillating with a very small amplitude oscillation, but the moment we put a flow with a particular velocity ah we find that there is a change in the what is called the phase and they are becoming out of phase and that phase lag if we find out if we are able to find it out we can directly you know correlated with the flow rate of the liquid. Now this constant as we have said is unique for a particular geometry. Now there can be different kind of geometry as we have ah mentioned earlier. So, one ah possible geometry could be like this we have a tube like a bend like this and here we can take a diversion and bifurcation and it could be another you know tube ah parallel tube each other. So, when there is a flow coming here it is getting bifurcated into 2 and we can put a sensor over here we can ah you know ah sensor on this side and on this side.

So, which will pick up the ah like inlet and outlet we have the sensors and here we can excite it with a small you know ah force this small force that we have said that we have a very small power requirement for this and that power requirement is basically to you know excited with a particular frequency and very close to the resonant frequency. So, that we have a very small amount of you know energy that will be necessary and these 2 ah sensors will pick up the ah you know oscillation at the inlet and the outlet. So, when there is no flow this inlet and the exit both will be in phase, but the moment you are putting a flow you can see that this will be you know ah oscillating like ah this will be coming very close, but this will be ah you know far off ah, but in the other part of the oscillation you will find they are moving apart and they will becoming very close. So, there would be an asymmetric oscillation ah. So, there are quite a few companies in the ah and those videos are also available online you can have a look into it.

So, that will be about ah say this kind of ah I mean ah it will for this one also it will be related ah by a relation qm, but this time we will have a some other constant C1 and tau. So, the C1 for this kind of arrangement where it was a straight tube is different for a double you know ah tube like this. So, this constant, but if it once it is known and calibrated we can theoretically ah calculate this C1, but ah in practice you know we calibrate it with the ah particular flow rate and once we do this calibration for a particular ah ah configuration we can use it for different fluid flow. So, that is about the Coriolis flow measurement ah. Then we can ah also talk about let us as we have said that we will also talk about when it is in the two-phase flow and then we have to determine it is quality and ah let us move to the quality measurement before that we will ah look into the different nomenclature and definitions of this quality.

And we have said for a particular mass flow m ah we have m is the mass flow rate and this is the total mass flow rate of the fluid and it is comprising of ah you know liquid phase mf and ah mg that is in the vapor phase. So, that is what is the total mass flow rate and now ah for the ah what is called ah corresponding volume in terms of the volume we have total volume V and ah Vf plus Vg are the two components in it ah we can ah here we have determined I mean define the quality as the fraction of the mass which is in the vapor phase. So, mg is the mass which is there in vapor phase and how much what fraction of the total mass that is in the vapor phase is called the quality. But the moment we put it in terms of the ah volume we have the liquid volume ratio ok. So, that liquid volume ratio is defined by the fraction of the total volume that is in the liquid phase.

So, that is why it is the liquid volume ratio it is in terms of the volume and it is in terms of the ah liquid volume. So, that is why Vf this is basically Vf by Vg ok. So, once we know that ah Vf ah and ah I mean we have been given this total mass flow rate we know and we know the total volume at the volume of it. So, we have to find out how much is the x and how much is the y. So, if we have to find it out we ah you know ah let us look into the other relations ah in terms of the x and y I mean the different parameters like we have the density we have said the density of the fluid rho equals to m by V.

So, let us look into the ah I mean m by V how we could be expressed ah. So, in terms of y we can put it as y equals to ah I mean the rho equals to y into rhof plus 1 minus y into rhog. But in terms of x we can put it 1 by rho equals to x by rhog and 1 minus x by rhof. It is not very difficult to ah I mean ah estimate it say if we ah try to calculate say for example, this first relation this is rho equals to m by V. Now we can put m equals to mg plus ah that is equals to m ah f and this total volume is of course, V.

$$\rho_f = \frac{m_f}{V_f}$$

$$\rho_g = \frac{m_g}{V_g}$$

So, let this be the V. So, this is mg by V and this is mf by V. Now, we will define another 2 parameters rhof and rhog in as defined the liquid density that is rhof equals to mf by Vf and the rhog equals to ah mg by Vg. So, this rhof and rhog are related by this relation. Now, in that case we can put this one as say mg let this be rhog and Vg this is rhog into Vg by capital V plus mf ah that is this f is ah you know rhof into ah Vf by capital V.

$$\rho = y\rho_f - (1 - y)\rho_g$$

So, this rho Vf by V already we have learnt about this in the previous slide that is equals to y and y into rhof. So, here this is rhog, but Vg by V we have not defined anything, but we can put it as V minus Vf by Vg the total V I am sorry. So, this Vg is equals to basically ah total volume we have defined is as Vg plus Vf. So, ah if we are replacing this Vf as V minus ah sorry V this is ah Vf this has to be I am sorry this Vg we are talking about we we are talking about here. So, rhog multiplied by V minus Vf by V.

$$\frac{1}{\rho} = \frac{x}{\rho_g} + \frac{(1 - x)}{\rho_f}$$

$$x = (1 - y)\frac{\rho_g}{\rho}$$

So, this can be ah written as y rhof and now you see ah this is rho g, but this is 1 minus Vf by V is basically y. So, ah this is how we have derived it ah in terms of the y. The other way you know the similarly 1 by rho if you are trying to find out this 1 by rho is basically V by m and here in this case we will replace this V with ah Vg plus Vf by total m and ah this total m is what this total m is basically rho into V. So, we put it as Vg plus Vf by m as you know ah rho into V. So, this can be written as ah let us try to put it like this say Vg by ah ah what is called rho into V plus Vf then you have rho into V.

So, ah in terms now we have to ah relate it in terms of x. So, what is that value of x? So, we have seen that x is basically ah m g by total m ah. So, this m ok we we would not in that case substitute this m ah instead of that what we have to ah do is like this say Vg by ah m we will write and we will also put it as Vf by m and in that case this Vg we will replace it with ah ah it would be ah Vf. So, it is basically ah mf by ah m and this will become 1 by rhof and similarly this Vf ah we will put it as plus Vf would become ah I am sorry Vg would become ah mg by m into 1 by rhog. So, now you see this mg by m is basically the x part.

So, from here we can see that 1 by rho is equals to ah 1 by rhog and then you know mg by m is basically the x. So, we got this term then the other term is m f. So, this mf by m we do not have any parameter, but m f we can write it as m minus m g like you have written it earlier in terms of V and this V equals to 1 by you know this is 1 by rhof. So, this would become x by rhog plus 1 minus 1 minus mg this is basically 1 minus x by rhof. So, what we have 1 by rho is equals to x by rhog plus 1 minus x by rhof.

So, that is how this fluid density can be ah correlated, but why are we doing this ah basically later on we will try to find out ah you know this x and y in terms of the density ah. So, let us try to look how do we do that. So, in order to ah basically find out this the values ok. So, this is what is ah let us ah try to look into this definition again. So, here this is ah the definition of x in terms of this 1minus y and also ah sorry this is ah ok fine.

So, this is how it is ah now let us move forward to the determination of this quality and for that we have a quality measurement instrument. So, where we have an inner rod ah and there is a you know outer ah container sorry outer pipe they are basically coaxial one, but the inner rod and the outer rod they are not ah connected electrically there you know ah this is an insulating support system, but what we are trying to find out is again the capacitance. So, the capacitance between these 2 rods, but you see we have ah slightly the enlarged the diameter of this ah outer casing ah you know this flow was coming here with a particular diameter now we have changed the diameter to a larger ah value because we are having an inner rod which is causing ah some flow obstruction. So, that I mean eventually what we ensure is that the cross-sectional area that we have here and this annular space they are the same. So, there is no sudden expansion or there is no sudden contraction at the entry and at the exit.

So, this cross-sectional area and the annular space between the inner rod and the outer casing they remain the same. And then we try to find out the capacitance between this 2-ah rod. Now, earlier ah while talking about the capacitance ah gauge we have seen that ah the capacitance of a ah I mean ah when we have 2 fluids the dielectric constant of the gaseous ah vapor ah vapor and the liquid they are different. So, we try to ah you know ah use that property here say if it is having 2 phase flow ah we will have you know the dielectric constant. So, we will here measure the ah capacitance and this capacitance again will be comprising of 2 factors.

$$C = \frac{2\pi L\epsilon\epsilon_o}{\ln(\frac{D_o}{D_i})}$$

So, ah this is the formulation we have learned earlier that this ah 2 pi L epsilon 0 into epsilon and ah ln D0 by Di. So, this capacitance we are measuring. So, from that capacitance we are calculating this epsilon because this length of the ah measuring unit is known D0 and Di basically ah if we look at this is the D0 and ah this is the Di that is the ah diameter Di is the diameter of the inner rod and D0 is the inside diameter of the outer casing. So, now we have said that ah we have gotten the value of the capacitance and capacitance from which we will calculate this dielectric constant. Now this dielectric constant because the length all other parameters are known.

So, once we know ah this and epsilon 0 is of course, the permittivity of the free space. So, ah we have now determined the epsilon and once we know the epsilon we can try to correlate it with the epsilon f and epsilon g. So, this is basically ah the way we have derived earlier the expression for way we can also you know put it in terms of the ah what is called the dielectric constant of the liquid and this is the dielectric constant of the vapor. So, earlier this was the density now we have the dielectric constant. So, we have this relation we have already determined this value and ah because from the measurement we have calculated the C and from C we have calculated the epsilon.

So, once we know the epsilon we can try to find out the y because epsilon f and epsilon g are known. So, this is equation 5. So, now if we look at we can find out that ah epsilon f and we can just rearrange this equation to find out in terms of the epsilon f we will directly get 1 minus y in terms of epsilon f and epsilon this is epsilon that we have measured epsilon f and epsilon g are the one which is already known. So, that means, we have already obtained 1 minus y. So, if we know 1 minus y we can also you know find out the y value.

$$\epsilon = y\epsilon_f - (1-y)\epsilon_g$$

So, from equation 1 now we see that the density which we have already said that rho equals to y into rhof ah plus 1 minus y into rhog. Now, 1 minus y we can replace it from here and you know this will become ah I mean again this can be rearranged where you know addition of this ah or slightly rearrangement will be ah giving this value. So, here also you see why are we putting it in this particular format because we have already obtained 1 minus y and directly we will put that value over here. So, from equation 3 earlier we have seen that this is the ah x value and x can also be written in terms of 1 minus y rhog by rho. So, already we have obtained rho from here ah because we have obtained 1 minus y.

So, once we have obtained 1 minus y we can put it over here and the density has already been known. So, we can now find out the quality the x. So, this is how this quality of any ah 2 phase flow can be determined and it of course, you can understand that it depends on the accuracy with which you can calculate the capacitance. So, that is about the quality measurement ah and these are the following references, but this reference particularly is for the Coriolis flowmeter where different type of you know Coriolis configuration has been given you can you know refer to that. So, thank you for your attention.