Cryogenic Hydrogen Technology
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Week - 05
Lecture 21
Basics of Cryogenic Liquefaction

Welcome to this lecture on Cryogenic Hydrogen Technology. We were talking about the production of hydrogen, then we have talked about the typical storage and with a with an emphasize that we are storing this hydrogen for fuel cell-based vehicle and we have looked into the different storage options. We have talked about the compressed hydrogen storage, then we have talked about the I mean liquid and then metal hydride and adsorption storage. But there is a also another possibility of storing it with the liquid condition that is liquid hydrogen. So, this liquid hydrogen we already know that it is basically a cryogenic fluid and we have to I mean then look at the liquefaction of hydrogen. So, if we have to look ah I mean if we have to liquefy hydrogen. So, what would be the process of liquefaction, then we have also looked into that ah I mean I mean when while talking about the ah properties of hydrogen we have seen that there is a concept of ortho to para conversion and we have to take that into account. So, let us look into this cryogenic liquefaction and these are the I mean ah concept that will be covered in this lecture and the typical ah I mean keywords are like ideal liquefaction cycle then liquefaction performance parameters and so on. So, initially we will be talking about the generalized cryogenic liquefaction and then later on we will come to ah specific problems like in hydrogen liquefaction and so on. So, ah let us start with ah not liquefaction let us look at the difference between the liquefaction and the refrigeration

So, whenever we talk about ideal refrigeration cycle ah we we call I mean we take the name of a Carnot refrigeration cycle. So, that is what is the ideal refrigeration cycle and we now we are talking about liquefaction. So, are they basically different in terms of thermodynamics definitely they are different. So, while a refrigeration cycle is a closed cycle the liquefaction cycle is an open cycle and ah that means, ah, but is there any ah similarity between these two. So, when we talk about the ideal refrigeration cycle ah I am sorry this ideal liquefaction cycle refrigeration cycle we say it on the T-S diagram if we ah put it we will find there are two isothermal processes and there would be two isentropic process.

So, between 1 to 2 we will have isothermal compression followed by isentropic expansion then we have between 2 to 3, 3 to 4 and again 4 to 1. So, we have isothermal heat addition, isothermal heat rejection this is heat addition and isothermal heat rejection and there is there are two ah isentropic expansion and isentropic compression. So, this total thing ah on the T-S plane ah is basically the ideal refrigeration cycle and on the P-V diagram also you will find ah we have ah I mean it is equivalent is there on the ah P-V plane. So, it is like we have this kind of ah surface I mean then you know 1 to 2 this is isothermal compression then expansion then we have again ah between 3 to 4 isothermal heat addition and then 4 to 1 is again an isentropic compression process. So, this is how ah this you know ah ideal refrigeration processes or Carnot cycle will be taking place, but ah if this is where we are rejecting heat QR and this is where we are absorbing heat.

Now, why are we looking at this refrigeration cycle when we have to look into ah liquefaction cycle. So, it is because that we will be taking a part of it because ah here we have seen that there is ah isothermal compression and why isothermal compression because that is ah you know then ideal compression process where the work requirement will be small and then it was followed by an isentropic expansion. So, basically if you look at ah we want to spend less amount of work and get the maximum benefit out of it. So, that is why you know we talk about isothermal compression followed by an isentropic expansion. So, ah that that means, if we take only this part of ah this cycle that would do our job ah I mean ah if we have been able to compress it and expand it you know to a state point where it will give you the liquid that is why we that is what we are looking for we do not have a closed cycle and we need not you know add heat and it would not be a basically a closed cycle it is an open cycle liquefaction cycle we are looking for.

So, that means, a compression followed by an isentropic expansion just half of the Carnot cycle is an ideal liquefaction cycle. So, that is what is ah the ideal liquefaction cycle. So, in the T-S plane when we have ah talked about ah you may remember that this is the you know vapor liquid dome and this is ah liquid plus vapor and this is these are the I mean ah isobaric lines. So, this is ah maybe you know depending on the fluid this may be the atmospheric line and this is the normal boiling point in that case. So, if we are somewhere here at the room temperature that is ah nearly around say depending on the ah I mean ah this is typically taken as 300 Kelvin or 298 Kelvin or so.

So, we have ah a gas at this ah point and what we do as we have learned that we will isothermally compress it fine. So, we will take it to a point when you know just it will be ah directly on top of this point. So, that means, if we expand it from this state point it should come to the saturated liquid condition. So, we have isothermal compression followed by isentropic I mean expansion. So, that would give us the liquid and then we can you know take the liquid out and use it.

So, this is what is a typical ah ideal liquefaction cycle. So, now let us look at the ideal liquefaction cycle as we have learned that there is a compression process ah followed by ah isothermal compression followed by an isentropic expansion. So, ah we will have a compressor that compressor will compress the gas ah to ah state point 2 from 1 to 2 as we have learned and then it will be expanded it will be the gas will be expanding and finally, we will have the liquid. So, that is how is the ah liquefaction ideal liquefaction cycle mdotf and we are of course, this mdot is equals to mfdot. So, the amount of gas we are compressing will be ah expanding.

$$Q_{net} - W_{net} = \sum_{outlet} \dot{m}\left(h + \frac{v^2}{2} + zg\right) - \sum_{inlet} \dot{m}\,(h + \frac{v^2}{2} + zg)$$

So, here we are spending energy this is the compressor ah and we are rejecting bound to reject some amount of heat from the system and this ah turbine or the expansion engine is generating some amount of work and that work will be extracted and it will help ah in compressing the gas. So, as a result this total ah work requirement would be or the total work is the Wnet which is basically the amount of work we are giving and ah there would be a lessening of this work by We. So, we will take it as Wnet we are rejecting heat Q_R. So, accordingly ah we can write the first law of thermodynamics for an open system that will be given by Qnet minus Wnet that is equals to summation of the outgoing ah energy con terms that is mdot h plus v square by 2 that is the kinetic part and the potential part is z into z minus this is for the outlets and then we have summation of mdot h ah v square by 2 plus z g on the in the inlet. So, this is how ah we can write the first law of thermodynamics for the ah I mean open system and this potential and the kinetic energy terms will be neglected usually.

$$Q_R - W_{net} = \dot{m}(h_f - h_1)$$

$$-\frac{W_{net}}{\dot{m}} = \left(h_f - h_1\right) - \frac{Q_R}{\dot{m}}$$

So, we will have basically the mdot and h of the outgoing hm part and mdot h of the incoming part. So, now, if we ah apply this on this cycle we can see that QR minus W net that would be equals to mdot and what is the outgoing enthalpy hf minus h1. So, that is what is the ah I mean total equation. Now, we can also write it as ah minus Wnet by mdot that is equals to ah hf minus h1 and ah minus QR by mdot. So, this can also be taken as h1 minus h1 minus hf minus QR by m dot.

So, here this W by ah W net by mdot that means, that is a ah parameter which we often try to put it or associated with the ideal liquefaction cycle. What is the work requirement per unit gas of you know the cryogenic fluid or the I mean gas that we want to liquefy? In the ideal liquefaction cycle whatever gas we are compressing that entire gas is getting liquefied, but in reality we will find the situation is different. So, at this moment we are trying to calculate what is the ideal liquefaction work requirement. So, that will be given by Wnet by mdot and that is equals to h1 minus hf minus QR by mdot. So, now, we need to look at this work requirement in the compressor.

$$Q_R = T_1(s_2 - s_1)$$

So, if we want to do that we assume that this compressor is first of all isothermal compressor and there is no irreversibility. So, that is an ideal ah cycle and it is the compression process is ideal there is no ah irreversibility. So, it is an ah reversible isothermal compression. So, in that case QR the work I mean the amount of heat that is getting rejected would be ah T1 into ah s1 minus s2 and ah that can be I am sorry this would be the final minus initial s2 minus S1. So, that is equals to ah T1 is the inlet temperature.

$$-\frac{Q_R}{\dot{m}} = T_1(s_1 - s_2)$$

$$-\frac{W_{net}}{\dot{m}} = T_1(s_1 - s_2) - (h_1 - h_f)$$

So, we can write and there would be of course, m dot. So, QR by mdot with a negative sign it would be ah T 1 into s1 minus s2 and then you know this minus QR by ok. So, this is a negative term taken into ah this side. So, the total equation ah would become then ah minus W net by mdot is equals to T 1 into s1 minus s2 and ah minus ah there is a negative sign here this negative sign minus h1 minus hf. So, this is the complete ah expression for the the minus W net by m dot.

So, why did we keep this negative sign on this Wnet? It is because the work is done on the system and that we take it as ah negative ah you know quantity. So, this as such will be a positive part and we have this expression for the total work requirement T 1 into s1 minus s2 minus h1 minus hf, where hf is the enthalpy of the ah saturated liquid and h1 is the enthalpy of the gas which is entering the system, h2 is the enthalpy of the compressed gas and we have ah s1, s2 and h1, hf. Now, if we look at this ah ideal liquefaction cycle we will find that we have this ah this is how it looks like this is 1 to 2 I am sorry this is an compression ah you know isothermal compression then followed by expansion this is not there ah. So, this is coming directly to point f. So, this is T this is S and here we see that ah the work requirement that we have calculated the Wnet by mdot equals to T1 into s1 minus s2 minus h1 minus hf.

$$-\frac{W_{net}}{\dot{m}} = T_1(s_1 - s_f) - (h_1 - h_f)$$

Now, here we find that s2 and sf are the same because this is an isentropic expansion. So, as a result we can write it as T1 into s1 minus sf and ah h1 minus h2. So, that is the work requirement of an ideal liquefaction cycle and ah this is sf is the entropy corresponding to the saturated liquid this is sf and sf equals to s2. So, let us try to calculate based on this expression, but is the ideal requirement ideal work requirement for the hydrogen liquefaction cycle. So, ah you can understand that we need ah to know actually what is the initial entropy enthalpy and or that means, what is the starting point.

So, if we take it as 300 Kelvin and then you know this is determined already it is known if it is atmospheric pressure. So, if we are starting with ah atmospheric pressure. So, it will come to 20.3 Kelvin and what would be the ideal work requirement that ah it is getting compressed and then you know it is expanded. Though it is not a practical cycle because this state point 2 would be ah ah I mean needing a kind of ah pressure in the gigapascal range not only that there is no you know expansion device which can take it from the gaseous state to directly liquid state 100 percent liquid state ah ah in an expansion engine ah it is not possible.

So, this is not a practical cycle, but still you know when we want to look into the actual cycle we need to compare it with respect to this ideal liquefaction cycle. So, let us look at the ideal work requirement. So, we are starting from 300 Kelvin and we are ending at the saturated liquid at 20.3 Kelvin. So, what are the things that we need to know this T1 has already been said we have to calculate s1, sf, h1 and ah I am sorry this is hf.

So, these are the things we have to calculate. So, we will take help of that chart that we have talked about this is of course, up to 100 Kelvin. So, we will ah look into the other one where we have said that this is you know at 300 Kelvin. So, ah the 300 Kelvin and 1 atmospheric pressure. So, this is where we have the enthalpy ah curve and this is at h equals to 4200 joule per gram.

So, we will have a ah what is called this is an enlarged view we can see that this is corresponding to this 300 Kelvin and this is the corresponding enthalpy. So, this enthalpy is 4200 joules per gram and the corresponding value ah on this side will be the entropy. So, if we look at this is where you know the entropy part this is joules per gram Kelvin this is 65. So, we have to take this value this is 65 joules per ah gram Kelvin. So, we have these 2 values for ah the room temperature at 300 Kelvin and let us look into the sf and the s ah this is s1 of course, and we need to now look at the hf and sf.

So, here at this is the graph and this is 20 Kelvin the 1 atmospheric pressure line is somewhere here this is the 1 atmospheric pressure line and this is this liquid vapor dome. So, we can see somewhere here we have this minus 500 ah joules per gram mole that is you know the unit and this is at this enthalpy is at 500 joules per gram mole this is minus 500 joules per gram mole. So, and the corresponding entropy is somewhere here around ah you know 18 ah joule per gram mole Kelvin. So, with this ah ok. So, here we can see that this is minus 500 and if we take this is the liquid vapor dome we have somewhere here ah and we have this point at which we have to take this entropy.

So, the corresponding enthalpy is 500 joule per gram mole. So, this ah it conversion of unit you have to take into account. So, to calculate the ah I mean enter calculation let us try to ah you know summarize it that hf we have taken as minus 500 joule per gram mole unit and h1 is ah 4200 joule per gram. So, if we convert it into joule per let us take it everything in joule per gram this will become minus 500 divided by 2.02 joule per gram now and this would become minus 247.5 joule per gram. So, this is for hf and for h1 we have seen that this is straight way ah it is giving us in terms of joule per gram. And now let us look at the sf we have seen it to be 18 joule per gram mole and ah this we can convert it into joule per gram per kelvin and this would come 18 sorry 18 by 2.02 joule per gram Kelvin and this would come as 8.91 joule per gram Kelvin. And we have also s1 corresponding to this we have ah if we look at we have the corresponding value we have said it to be 65 joule per gram and Kelvin.

So, now if we ah put all these values you will find it is coming as ah T1 into s1 minus sf minus h1 minus hf that would give us minus Wnet by mdot that is the work requirement for ideal liquefaction cycle and that would be you know as per this ah 300 multiplied by 65 minus 8.91 minus h1 minus hf. So, that is 4200 and this negative of negative that becomes positive 247.5. So, the total part is 12379 joule per gram or kilo joule per kg.

So, this is 12379 kilo joule per kg is the work requirement per unit ah per kg of gas compressed. So, in that case ah this is you know as per the ah what is called you have to keep it in mind two things. First of all, we have used a chart that is meant for the para hydrogen, but when we said that we are starting at 300 Kelvin. So, it is obviously, normal hydrogen. So, you are supposed to take the property of normal hydrogen at that point and we are also supposed to calculate the properties at the for the normal hydrogen at the liquefaction point.

So, accordingly the you know if you look at the Barron’s book you will find this this ideal work requirement will come out as 12019 kilo joule per kg. So, we will use this value for the ideal work requirement provided this gas we have started at 300 Kelvin and one atmospheric pressure. If it is changed I mean if this initial condition is changing obviously, the end result will also change. So, that is about this liquefaction ideal liquefaction cycle and based on that we will look into the actual liquefaction cycles in the ah coming lectures. So, this is the ah I mean ah reference book ah these are the reference books I mean you can also look into the Thomas Flynn cryogenic engineering or the Barron’s book.

So, thank you ah for your attention these are the conclusions ah I mean the ideal liquefaction cycle we have talked about and the ideal work requirement we have ah you know calculated and accordingly we find that the ideal work requirement is about 120 ah 12019 kilo joule per kg of hydrogen. So, thank you for your attention.