Energy Conservation and Waste Heat Recovery

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Lecture – 27
Thermodynamic cycles for low temperature application

Hi everybody, we are again back to our lecture class on Energy Conservation and Waste Heat Recovery. Lastly what we were discussing, we were discussing regarding combined cycle power plant and one of the very successful and a very comprehensively realized from combined cycle power plant is a combination of gas turbine and steam power plant. In that connection I have also discussed a very unique a component of this power plant that is HRSG or heat recovery steam generator.

At the beginning I have given also different options of combined cycle power plant like the combination of magneto hydrodynamic and a Rankine cycle, similar examples have been given, but specifically there are certain combined cycle power plant which are suitable for waste heat recovery purposes. And the bottoming cycle of the combined cycle power plant some of this bottoming cycle can be used as standalone power, power generation cycle particularly when waste heat recovery is the concern.

So, in today's lecture to start with what we will do we will have an overview of the thermodynamic cycles their temperature range and from there we will try to figure out which are the bottoming cycles suitable for waste heat recovery purpose.

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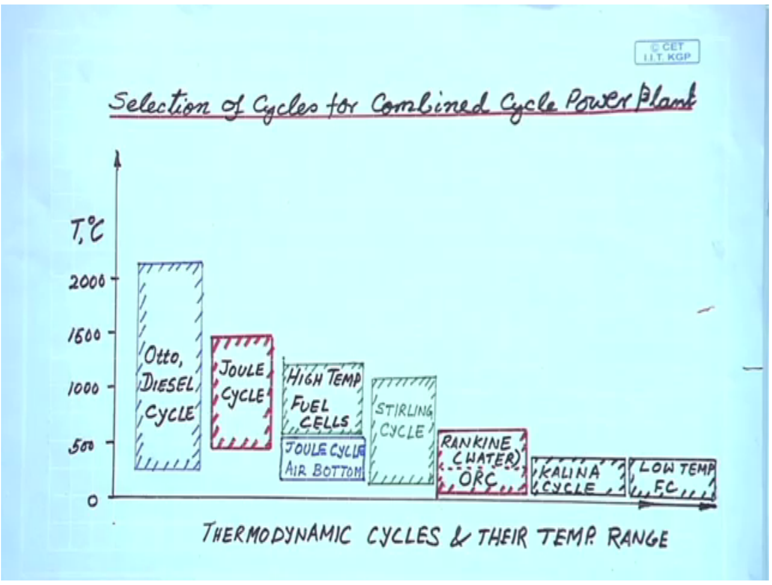

So, if we look into this slide different kind of thermodynamic cycles have been drawn and their temperature ranges have been mentioned. So, if you see the first cycle that is otto and diesel cycle the highest temperature could be very high it could be even more than a 2000 degree Celsius and the lowest temperature could be somewhere around a 250 degree Celsius or even slightly lower or higher.

Then there is Joule cycle which is nothing, but your gas turbine cycle then high temperature fuel cells then there is air bottoming cycle have some sort of a joule cycle is possible then stirling cycle, then Rankine cycle and in case of Rankine cycle you see the low term temperature limit is almost close to 0, so it could be of the order of depending on the a climatic condition. It could be of the order of 30 degree, 40 degree, 20 degree or even lower in cold countries.

Now, in the Rankine cycle you will find at the top I have written Rankine cycle where working fluid is water. At lower temperature range same Rankine cycle almost same construction can be utilized same thermodynamic cycle can be utilized, but the fluid will be different means fluid will be other than water it is organic Rankine cycle we are going to spend some time on organic Rankine cycle in some of the lectures. Then there is Kalina cycle then there is low temperature fuel cell. So, these are the more or less options of main thermodynamic cycles. I do not want to give an impression that this is an exhaustive kind of listing of all thermodynamic cycles, but these are most commonly used thermodynamic cycles.

So, for waste heat recovery we have to look into a good cycles which operate at low temperature range. In some cases they can sub as the bottoming cycle particularly when there are different kind of energy options available and it is desirable to also explore different kind of energy options including renewables. So, we are interested in towards the bottom end; that means, the cycles which will operate at low temperature they can act as the bottoming cycle for a combined cycle power plant and they can act as standalone cycle for power generation in case of waste heat recovery or even in case of a renewable energy sources.

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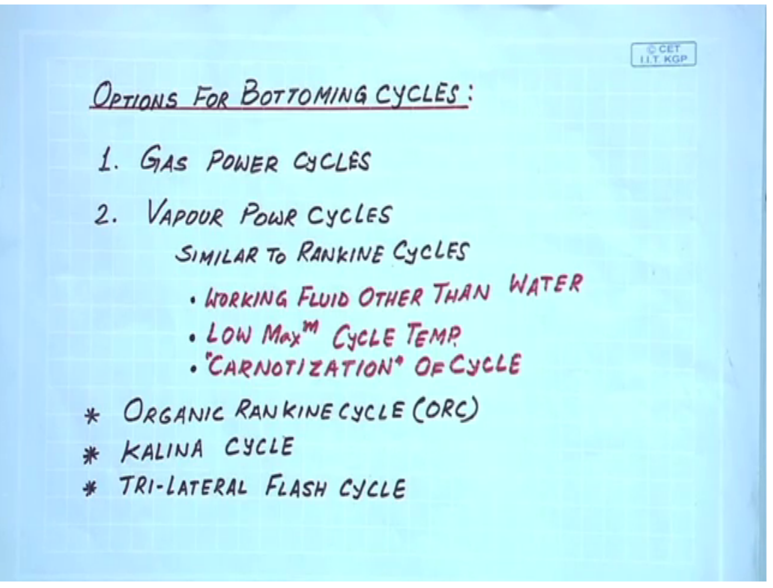

So, with this let me go to the next description option for bottoming cycle. So, this again I like to clarify that they need not be the bottoming cycle they could be standalone cycle for low temperature application. Like cycle suitable for waste heat recovery purpose. So, there could be gas power cycles like your dual cycle for air bottoming cycle they and there could be vapour power cycle. The vapour power cycles are the vapour power cycles are quite similar in principle and in construction with Rankine cycle, but there could be some sort of difference and these differences are working fluid other than water.

Water is a very good working fluid for vapour power cycle when the temperature range is relatively high it has got number of advantages, but at the same time it has got number of disadvantages also for temperature ranges beyond which normally steam power plant are used. That means, for a very high temperature it will have its limitation and for lower temperature where waste heat is available there also water will have limitation. So, we are interested in generating power from a low temperature heat source. So, working fluid other than water we will try to explore and for that the cycle modification that we will also look into what kind of cycle minimize sorry cycle modification is needed.

The second one is low maximum cycle temperature which I have explained. A low maximum cycle temperature again working fluid other than water will be suitable and when we are talking about working fluid we also we like to see that whether by using a typical working fluid whether we can have some sort of advantage some sort of leverage over the conventional Rankine cycle, this point I will elaborate when we will take specific cycle.

And then Carnotization of cycle what is Carnotization of cycle? We know that Carnot cycle cannot be used as a vapour power cycle because of a different practical difficulties practical limitation, but then a practical cycle which can be used can we modify it by either by modifying the cycle itself bringing some new components etcetera or by using a very a special kind of fluid. So, that it comes close to the Carnot cycle it will not be exactly equal to a Carnot cycle, but it will come close to a Carnot cycle.

Already, we have done this thing like when we go for regenerative feed heating to some extent we try to increase its efficiency by reducing the a heat addition to the cycle at low temperature. So, this is one step towards realizing higher efficiency and going one step forward towards Carnot cycle. So, generally three cycles are very important in this case. They have got lot of potential and some of them the top two have already been commercially exploited they are successfully running in different plants for renewable energy and for waste heat recovery.

They are organic Rankine cycle in short form it is known as ORC, a Kalina cycle and tri lateral flash cycle. So, these cycles these are vapour power cycle close to Rankine cycle we would like to discuss we would elaborate on these cycles.

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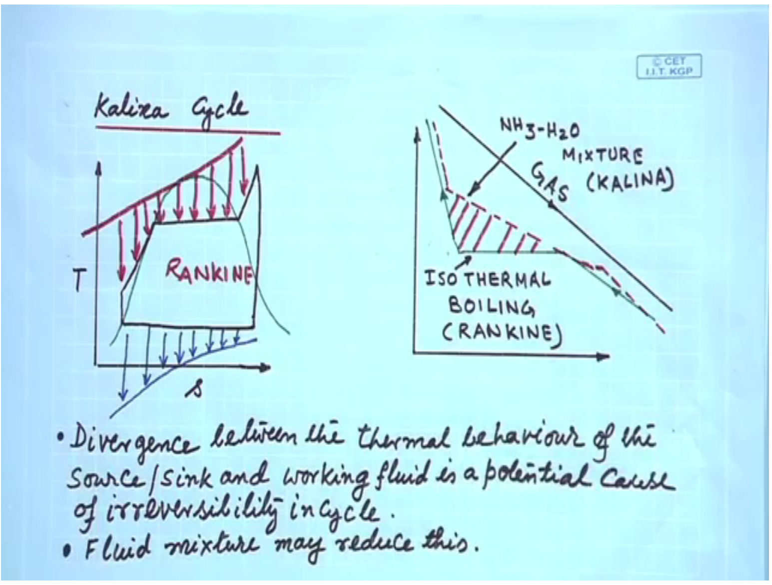

So, first we start with Kalina cycle we start with Kalina cycle because out of these cycles three cycles I have told Kalina cycle, organic Rankine cycle and the tri lateral flash cycle a Kalina cycle operates at towards the higher temperature. One can have large power plant with the help of Kalina cycle and it is one of the commercially proven cycle already in use in a number of application in number of countries.

So, to start with on the left hand side I have shown a classical Rankine cycle. So, this is the steam dome and or two phase dome and this is the classical conventional Rankine cycle without any modification with ideal processes. Now, like any other heat engine cycle it has to take heat it has to take heat from high temperature flue gas high temperature gas will cool down the gas will have a path like this and the Rankine cycle the fluid is getting heated up.

So, conventionally as it has been done a many a times during our first discussion. So, conventionally we are showing some sort of a counter current flow type arrangement between these two streams. And similarly in the condenser we have got the steam condensing almost at constant temperature and then there is condenser cooling by with the help of a water. So, the water is getting heated up the curve is something like this here also I have found a counter current flow like arrangement.

Now, in both the cases what we can see that the temperature change of the working fluid and the temperature change of the fluid which is acting either as the source or the sink they do not match very well. So, there are large temperature gap at places. So, what we can say that divergence between thermal behavior of the source sink and working fluid is a potential cause of irreversibility in the cycle. So, this we have already discussed many a times that heat transfer across a finite temperature difference is a cause of irreversibility that gives loss in the cycle and then we cannot recover more amount of energy.

So, with this we can see both the heating and cooling process of Rankine cycle are not very conducive from that point of view. So, many a times one tries to change the Rankine cycle modified the Rankine cycle, so that we can follow this heating and cooling curve more faithfully. One of the ways by which we have done it already we have done in our already we have discussed in our previous lecture that is by using multiple pressure in HRSG we have done it.

Another way of doing it is that instead of a single fluid if we use a fluid mixture then these two cards can be changed let me explain it why. A single fluid or a pure fluid will boil and condense at constant temperature, but if we take a fluid mixture, mixture of two fluids then it will boil and condense over a temperature range. So, during evaporation and condensation its temperature will not remain constant and if that is true then we can have a good match with the heating curve or the cooling curve. So, this is the main point of a Kalina cycle. In Kalina cycle instead of taking water pure water as the fluid as we have taken in Rankine cycle we will modify the Rankine cycle because we have to take some sort of a fluid mixture and that fluid mixture could be any fluid mixture suitable for this purpose, but one fluid mixture one fluid pair has been very successful that is ammonia water solution.

So, ammonia water solution here we can see this is the cooling curve of the gas this is the conventional heating curve of a Rankine cycle with water as the working fluid and if we take $NH_3 – H_2O$ mixture that is Kalina cycle the curve becomes something like this and then this shaded portion you see this much energy saving is there. Or rather this much energy saving is there and we also reduce the irreversibility. Similar kind of a figure one can draw for the condensation side and we will see it.

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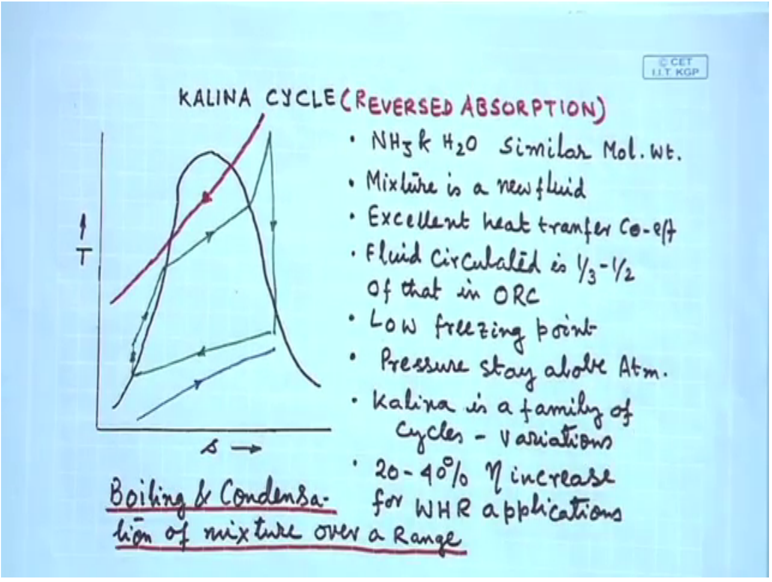

So, Kalina cycle sometimes it is also called reversed absorption cycle we are familiar with maybe some of you are familiar with absorption refrigeration cycle. So, this is a power cycle where absorption is being used now why ammonia and water NH 3 and water they have similar molecular weight. So, mixture that behaves like a new fluid and it has got excellent heat transfer coefficient.

Fluid circulated the mass of fluid circulated that is one third or half of that needed in organic Rankine cycle, organic Rankine cycle we are going to describe. So, you see the two cycles are more or less for the same kind of operation for the same kind of range, but in case of a Kalina cycle the mass flow rate could be quite small. So, certain fluid circulation, we have to handle less amount of fluid obviously, that will have its effect on equipment size equipment size can be made smaller.

Then low freezing point that is another advantage and pressures stay pressure stays above atmospheric pressure. So, that is what we are talking about the condenser pressure, you know in the turbine one has to expand from high pressure to low pressure and ultimately at low pressure heat has to be rejected at atmospheric temperature and at that condition the pressure is not very low. If the pressure is not very low then the difficult we follow in conventional Rankine cycle will be absent here; that means, in the conventional Rankine cycle in the condenser steam side will go below atmospheric pressure. So, that has got many problems of leakages and in this case the pressure stays above atmospheric pressure, so this is advantageous.

And Kalina, though we call it Kalina cycle, but Kalina cycle is not a single cycle. Basically using this kind of fluid mixture it need not be water ammonia water ammonia is mostly used and water ammonia is very successful fluid for this, but it could be any suitable fluid. Using this kind of principle we can have a host of different cycles even using ammonia water we can have different cycle designs and this cycle design one can have depending on the source temperature depending on the type of source we are getting, so it gives lot of flexibility. And then we are discussing regarding waste heat recovery application it is also relevant for a renewable energy source like a solar energy or particularly geothermal energy in that range a Kalina cycle gives 20 to 40 percent increase in efficiency it properly designed. So, this is a very good advantage of Kalina cycle.

So, left hand side now we go back to the left hand side left hand side I have shown the Kalina cycle. So, basically like Rankine cycle it will have one expansion in a turbine or an expand expander then it has to condense, it is condensing but mind that the condensation is not a constant temperature. So, it is as it is condensing its temperature is reducing, so obviously, it matches with the cooling curve of the cooling medium or cooling water whatever it may be. Then of course, there should be pressurized and then there will be heat addition.

Again like a Rankine cycle there will be heat addition in three different stages first the liquid will be heated then once it reaches the saturation temperature it will be evaporated and then it will be superheated. Now it will be evaporated when it is evaporated you can see that the temperature is not constant as the evaporation process proceeds the temperature also increases.

So, what it will give again it will give a good matching with the cooling curve of the fluid gas. So, a boiling and condensation of mixture that takes place over a range of temperature. So, this is the main advantage of Carnot cycle.

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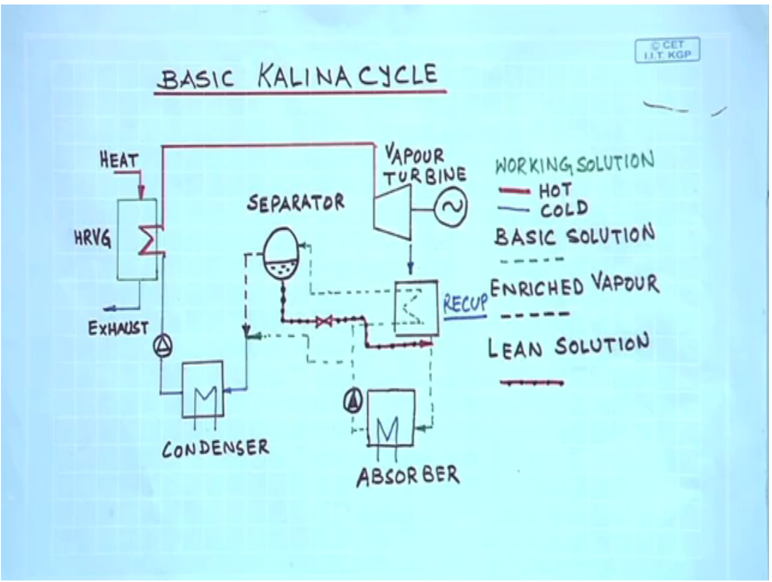

So, now I go for the description of Kalina cycle. As I have told that Kalina cycles are a family of cycles different designs are possible many variations of the designs are possible. Obviously, a designer of a Kalina cycle has to consider a many aspects including economic aspects the payback period etcetera and then the Kalina cycle has to be designed.

Now, here we concentrate on a very basic arrangement very base basic Kalina cycle very simple plant layout. So, what we can find here that we are having some sort of a component where the fluid picks of heat. So, the component where the fluid picks of heat is called HRVG or heat recovery vapour generator. Like your Rankine cycle it has also got four basic operation heat addition, expansion and then this total, this many combination of equipment can be taken for heat rejection and then there is some device for pressure rise.

So, if we see the component we will come back to the cycle layout once just right now, but we if we see the component. So, there is mixed air vapour will expand in the turbine or expander.

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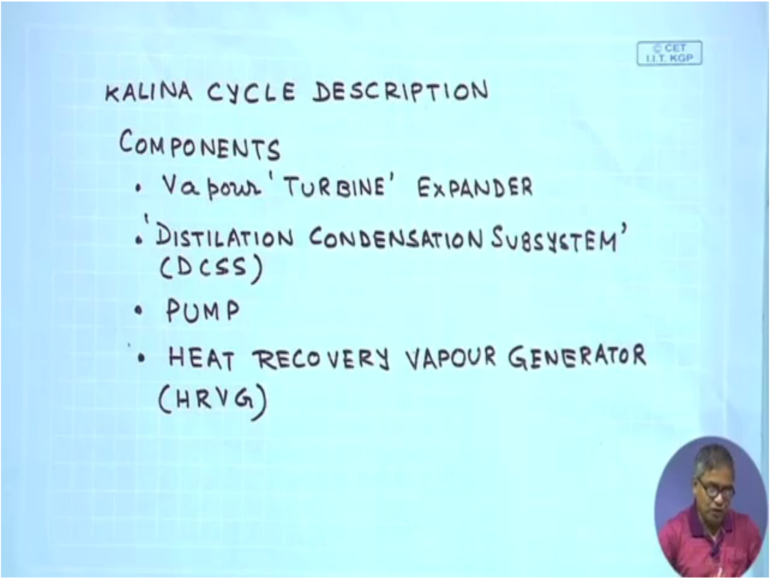

Then distillation condensation subsystem which takes care of after the expansion we have to reject heat and that heat rejection is taken care of by distillation condensation subsystem DCSS. DCSS I have shown again we will see then there will be some pump or raising the pressure and then there will be heat recovery vapour generator HRVG, either it will be a waste heat device or it could be some sort of a some sort of a renewable source of energy.

So, with this four this thing let us go back. We know there are four processes and vapour actually it will be a mixture of two fluids vapour mixture that expands to the turbine power is generated and then it goes to a recuperator. So, this is basically a recuperator, I am writing it in short this is a recuperator. So, in the recuperator there is heat transfer and this is some sort of energy saving device and in the recuperator you can see there is heat transfer between same stream; that means, this stream after some other process it comes back and in the recuperator there is heat transfer. Up to this if we like to describe then it is like this in DCSS, DCSS means this total thing is DCSS that is distillation condensation subsystem, stream that is mixture stream from the turbine is cooled first it is cooled in the recuperator. So, recuperator it is first cooling and then it is mixed with a lean solution of NH 3. So, this lean solution comes from the separator. So, here it mix with the lean solution and then it produces the basic solution this green dotted line is the basic solution.

So, once this is the basic solution it goes to, is it why this basic solution is needed because it ranges the temperature needed for condensation otherwise we have to condense the gas at a very low temperature. So, resulting basic solution is condensed in the absorber. So, here in the absorber it is condensed. So, after condensing we raise its pressure and mostly it goes to the recuperator.

So, you recuperator you see that almost between two same stream at, but the same streams are at different places of the cycle they are internally exchanging heat. So, here then what it will happen what will happen the pump is raising the pressure and after that this is slightly heated or partially it is heated this basic solution is heated. But while it is coming to the recuperator in between part of it is taken and part of it is mixed with the enriched vapour which is coming from the separator and from the recuperator the basic solution which has been heated whose pressure has been increased it goes to the separator and here it flashes.

If it flashes then it will produce vapour and also it will produce some amount of liquid. So, the liquid that is a lean mixture and this lean mixture is coming and mixing here after the recuperator what I have described earlier and then the vapour is coming here the vapour is enriched vapour and vapour is mixing with the basic solution then the mixture goes to the condenser and in the condenser it is condensed. After the condenser we have the pump for raising the pressure. So, that it can be sent to the heat recovery vapour generator to generate high temperature and high already pressure is high, high temperature vapour and the cycle continues. So, this is what we get from the Kalina vapour cycle.

So, with this let us come to the end of this lecture the other cycle which are based on your Rankine cycle principle that we will discuss in the coming lecture.

Thank you.