Chemical Process Utilities
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Lecture – 3
Power Cycle

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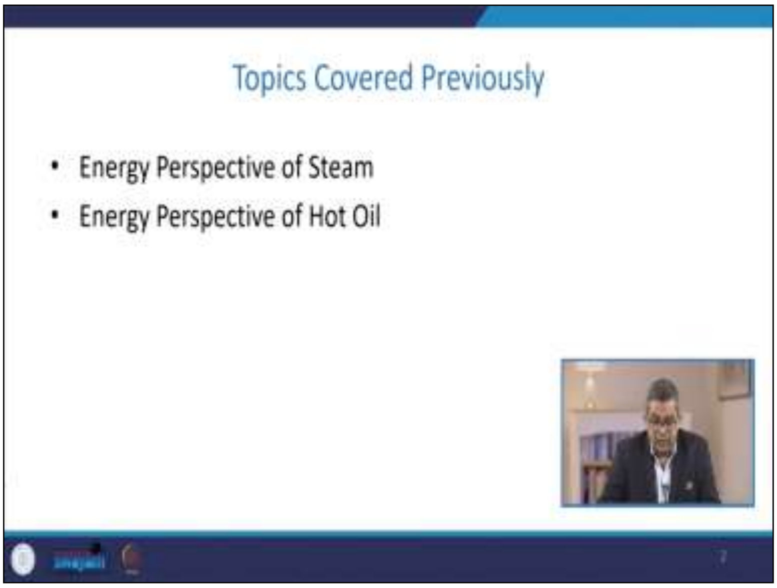

Welcome to the concept of power cycles under the head of process utilities. In the previous top lecture, we covered the energy perspective of steam and the energy perspective of the hot aisle. While discussing either steam or hot oil, there are certain factors that we need to consider, and those are attributed to the thermodynamics because while we are converting the water into steam, the thermodynamic clause all the thermodynamic laws attributed to this one previous.

Similarly, if we heat the hot oil from normal temperature to, say, 400-degree Celsius or 350-degree Celsius, then again, various kinds of thermodynamic laws come into the picture. So, while discussing this temperature dome domain or temperature governed parameters in various heat transfer-related systems, we cannot overlook the importance of various thermodynamics laws various thermodynamic cycles.

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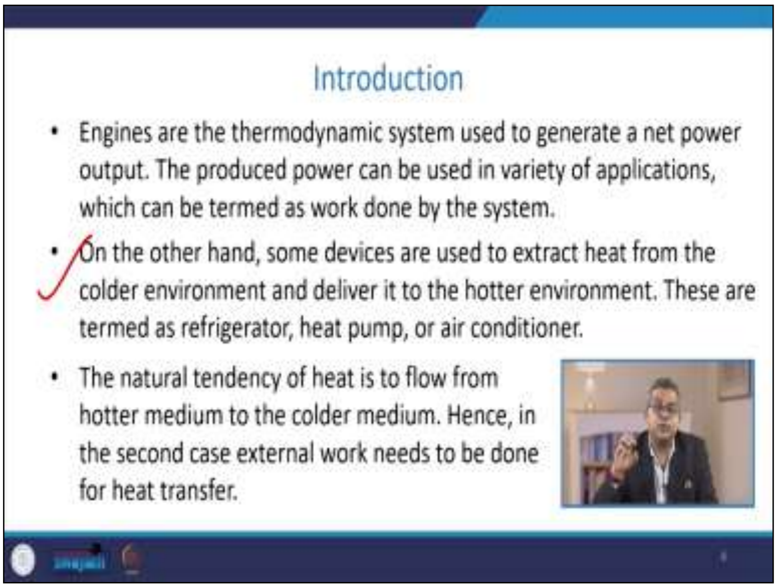

And especially, we all know that the various power generation and refrigeration aspects are always tutored by thermodynamic law. There are many cycles on date available through those tutored the power generation and the refrigeration concept. So, in this particular lecture, we will cover these thermodynamic cycles that are involved or theoretically attributed to power generation and refrigeration.

Now before we go into the detail of these thermodynamic cycles, you must know some introductory remarks like; the engines are the thermodynamic system used to generate the net power output. Usually, as consumers, we never bother about how this power is generated and what are the different principles involved in the generation of the power.

Now this produced power can be used in various applications, which can be termed as work done by the system; this is the usual thermodynamic law. On the other hand, some devices extract heat from the colder environment and deliver it to the hotter environment; these are termed the refrigerator. The best example is your domestic refrigeration system, and the next example is your domestic air conditioning system.

So, the natural tendency of heat is to flow from a hotter medium to a colder medium. Therefore, in the second case, some external work needs to be incorporated for the heat transfer to push out the excess heat to deliver outside. Now, however, both systems work on the principle of thermodynamic cycles; all we know is that the things are used tutored by these thermodynamic laws.

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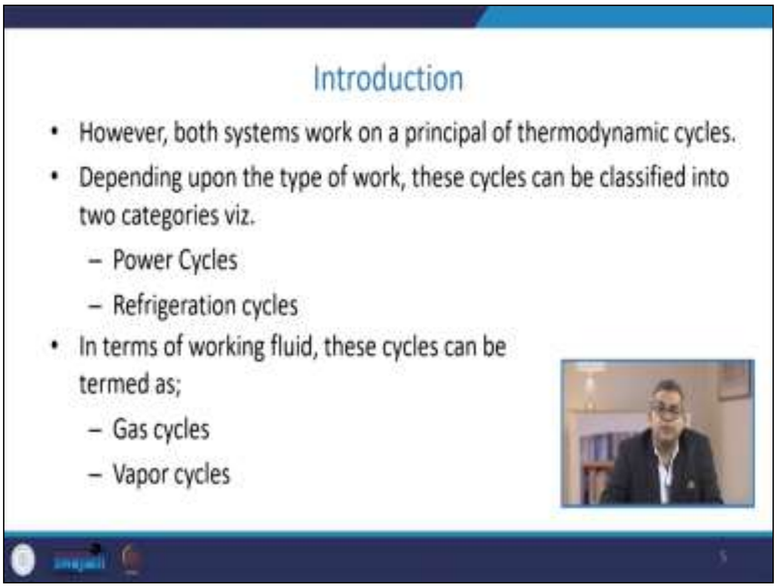

So, depending on the type of work, these cycles can be classified into two categories: the refrigeration cycle and the second is the power cycle. In terms of the working fluid, sometimes these cycles can be termed the gas or vapor cycles.

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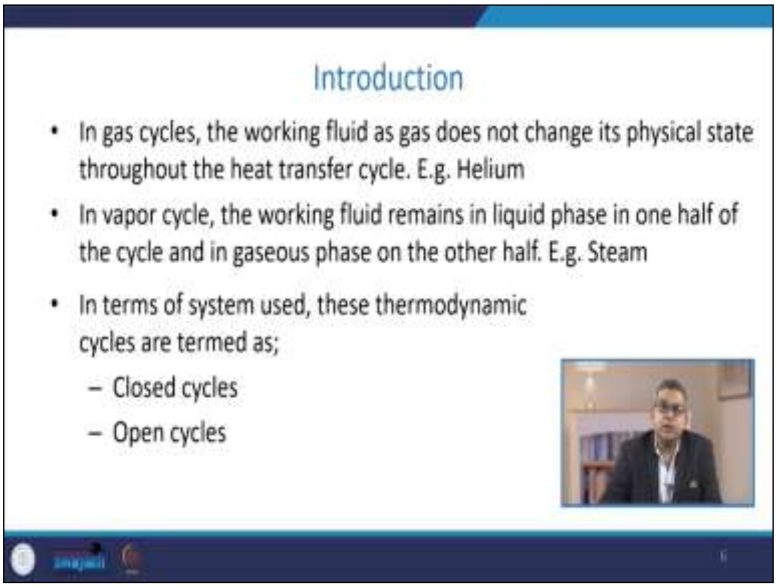

Now in the gas cycle, the working fluid as gas does not change its physical state throughout the heat transfer. So, this is again a very good very good added benefit, and one example is helium. In the vapor cycle, the working fluid remains in the liquid phase in one half of the cycle and the gaseous phase or in the vapor phase in the other half, like steam. So, we have to consider this phase change and in situ the volumetric change or latent heat whatever all these things into consideration.

So, in terms of the system used, these thermodynamic cycles are termed closed and open cycles.

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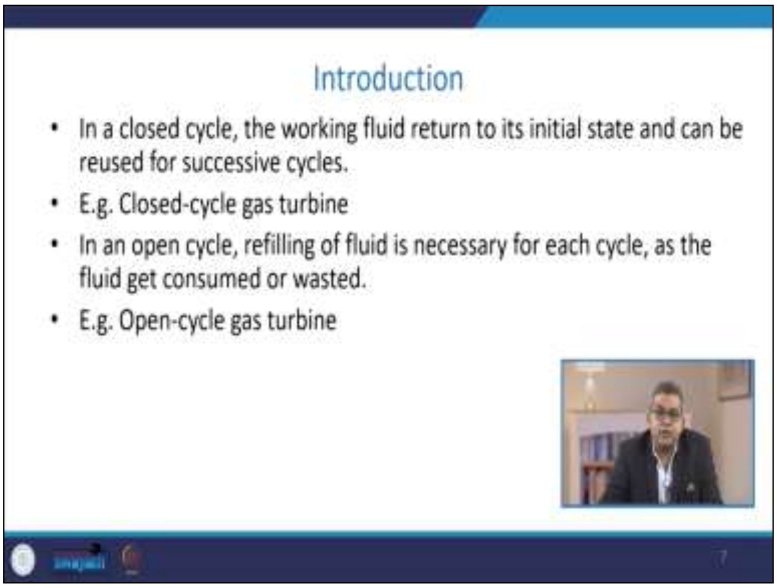

In a closed cycle, the working fluid returns to its initial state and can be reused for the successive cycle. So one example is a closed cycle gas turbine; we will discuss the theoretical aspect and subsequent slides. Now in an open cycle, fluid refilling is necessary for each cycle as the fluid may get consumed or wasted during the entire process, like open cycle gas turbines.

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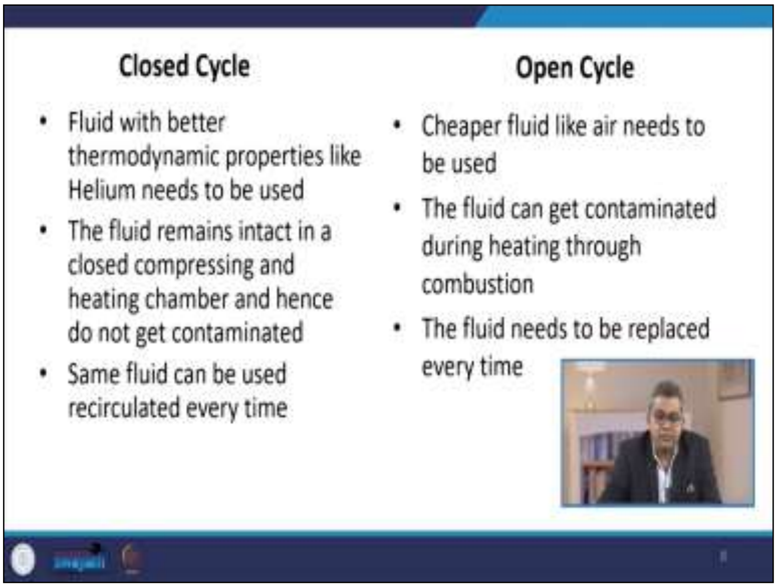

So, here you can see a comparison between the closed and open cycles. Now fluid in the closed cycle fluid with better thermodynamic properties like helium needs to be used, whereas in an open cycle, we can use cheaper fluids like air. In a closed cycle, the fluid remains intact in a closed compressing and therefore cannot get contaminated in due time.

An open-cycle fluid may get contaminated during heating and some processes. In a closed cycle, you can use the same fluid or recirculate every time this entire fluid. In an open cycle, you need to change the fluid or replace the fluid every time.

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Similarly, in the closed cycle, the fluid does not affect the system's life cycle: the wear of turbine blades, etc. So, a bit lesser, the cost towards the maintenance would be low or minimal. In an open cycle, contaminated fluid can affect the system's service life. So, the maintenance cost or wear and tear cost may be on the higher side. The closed cycle is preferable for stationary installation and marine uses whereas open cycle systems are best suited for moving installation.

Similarly, the closed cycle has high maintenance and installation costs inherent in the closed cycle. Whereas in an open cycle, maintenance and installation costs are a bit lower because of the variety of choices.

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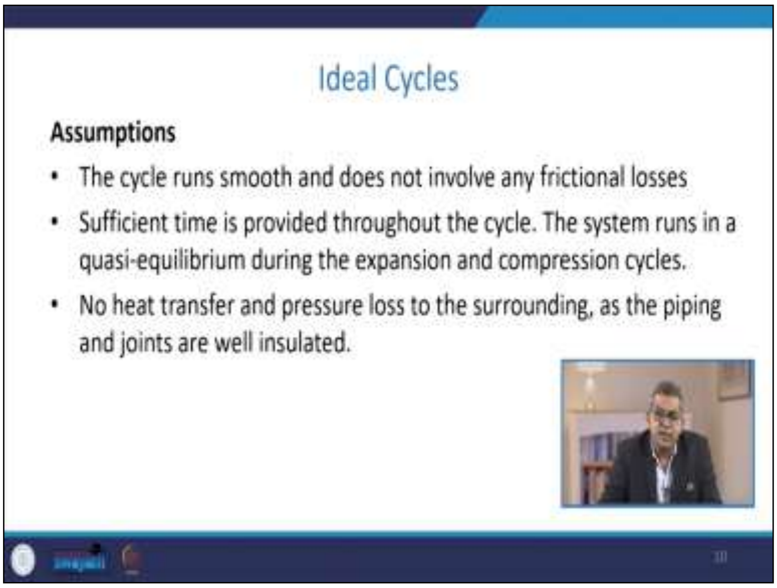

Now let us take the example because we are saying that we are tutored by these thermodynamic cycles. So, while considering the thermodynamic aspect, we must know the concept of ideal cycles. So, while considering the ideal cycle, certain assumptions need to be taken. This cycle runs smoothly and does not involve any kind of frictional loss and sufficient time is to be provided throughout the cycle.

The system runs in a quasi-equilibrium during the expansion and compression cycle, and there should be no heat transfer and pressure loss to the surroundings as the piping and joints are well insulated. So, these are the pure assumption with respect to the ideal cycle.

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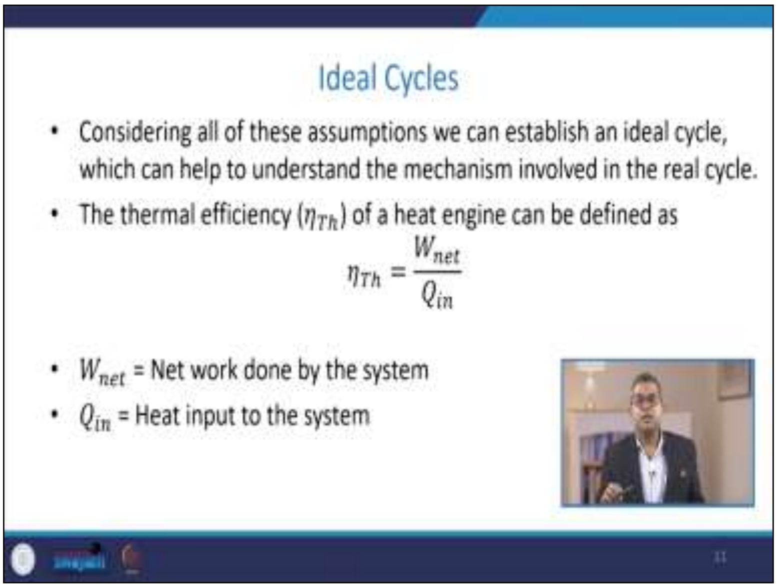

Considering all these assumptions, we can establish an ideal cycle that can help us understand the mechanism involved in the real cycle. Sometimes we are very much interested in the thermal efficiency of heat engines. So, this thermal efficiency of the heat engine can be defined as the net work divided by the heat input to the system.

$$\eta_{Th} = \frac{W_{net}}{Q_{in}}$$

- W_{net} = Net work done by the system
- Q_{in} = Heat input to the system

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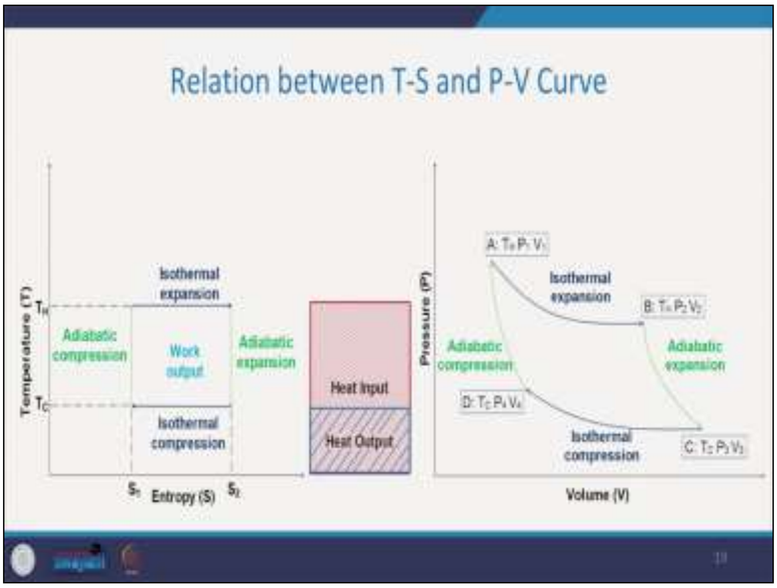

And you see that the Carnot cycle is very popular; Leonard Carnot proposed this. Now it gives a thermodynamic interpretation of the maximum possible efficiency that could be obtained from a heat engine. So, it put forward one limiting effect: gentlemen, you cannot go beyond this limit. So, whatever effort you are putting forward to surpass this limit will be futile.

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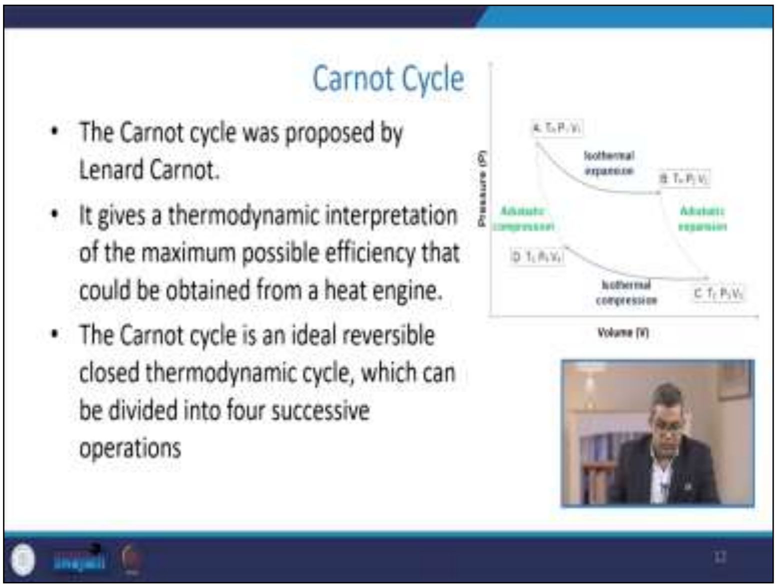

So, the Carnot cycle is an ideal reversible closed thermodynamic cycle that can be divided into four successive operations. The first one is the isothermal heat addition from the heat reservoir maintained at T_H leading to an isothermal expansion. So, this is this is the pressure and volume.

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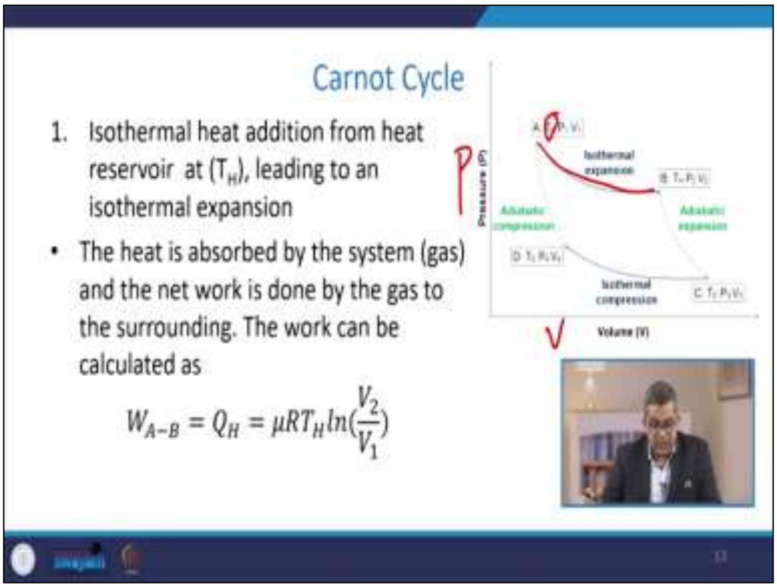

Now see an isothermal expansion; we are keeping the temperature constant. The gas system absorbs heat, and the net-work done by the gas surrounding this can be calculated as now from here this is the original station the system reached reaches to this station. So,

$$W_{A-B} = Q_H = \mu R T_H ln(\frac{V_2}{V_1})$$

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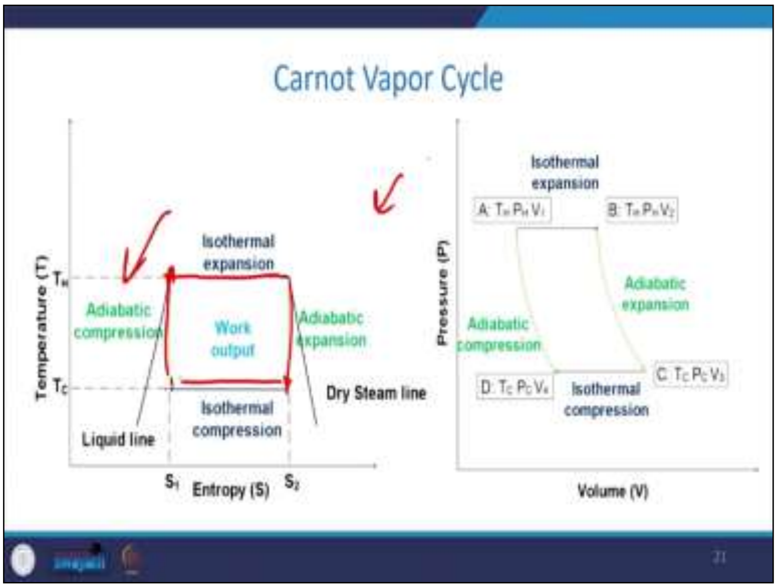

Now this is your V_2 and this is your V_1.

The work can be calculated as from a when the system moves from a station to b station. Now this V_2 is the final volume and this is the initial volume final volume with respect to this particular isothermal expansion.

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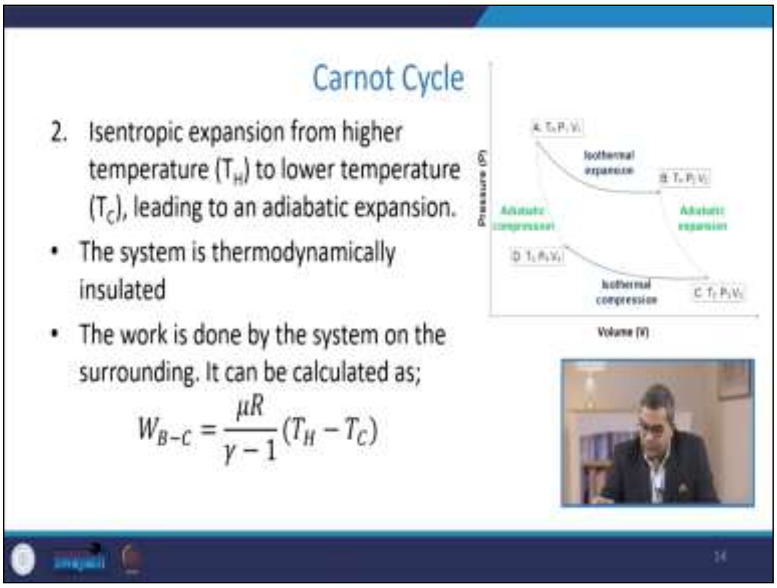

Now second is the isentropic expansion from higher temperature to a lower temperature leading to the an adiabatic expansion. So, this is your stage from station B to station C and you can calculate the work done during this particular course of time. So, from station work done from station B to station C,

$$W_{B-C} = \frac{\mu R}{\gamma - 1}(T_H - T_C)$$

Now I told you that usual thermodynamic law they are prevailing. So, this is an isentropic expansion. So, we are using this mathematical formula.

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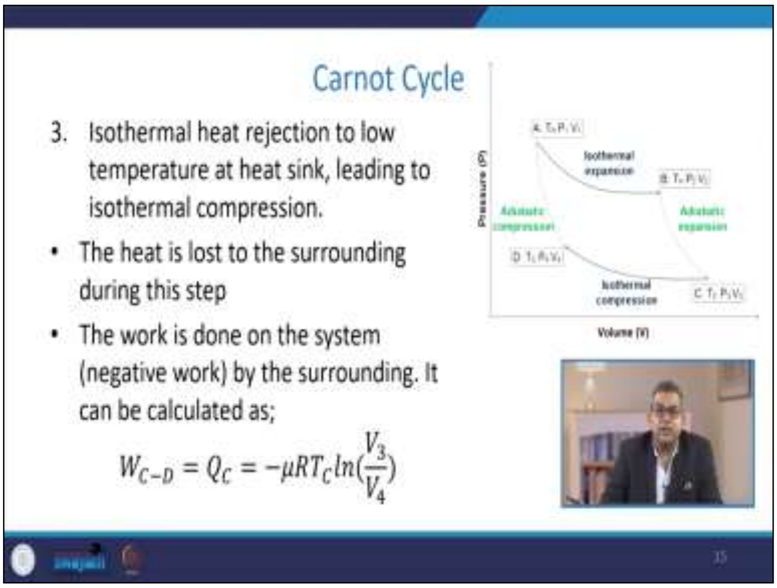

Now the isothermal heat rejection to a low temperature at heat sinks, leading to isothermal compression. Now, this is from station C to station D, right. Now the heat is lost to the surrounding during this particular step. So, while calculating the work done on the system again, the same phenomena from work done from station C to station D is equal to

$$W_{C-D} = Q_C = -\mu RT_C ln(\frac{V_3}{V_4})$$

Now this is the final volume for this step and this is the initial volume.

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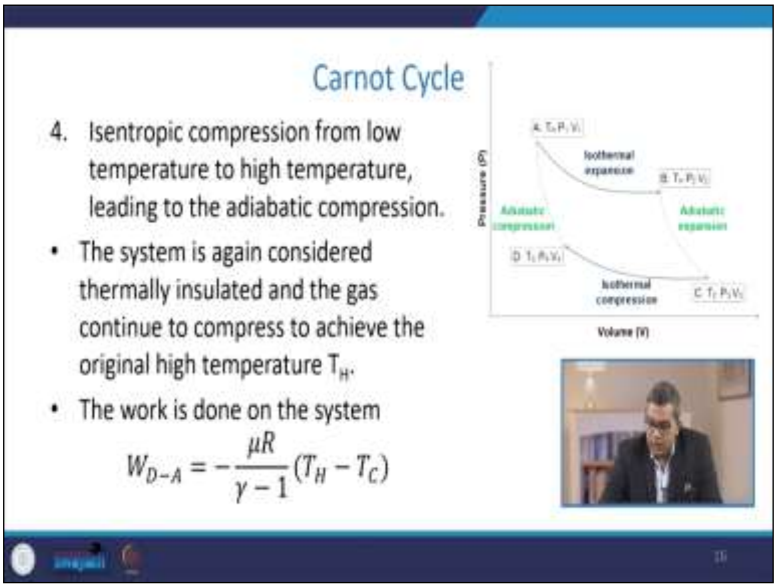

Now the isentropic compression or adiabatic compression from low temperature to high temperature leading to the adiabatic compression now this system again considered thermally insulated and the gas continue to compress to achieve the original high temperature. So, your entire with respect to that thing the entire cycle repeats. So, work done from station D to the station A from here to here is equal to

$$W_{D-A} = -\frac{\mu R}{\gamma - 1}(T_H - T_C)$$

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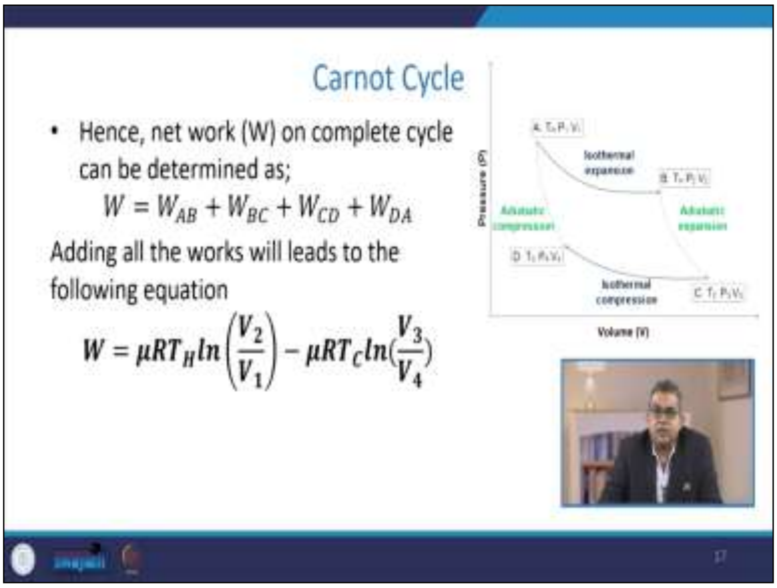

So, while calculating the net work on complete cycle this we can determine with this mathematical formula W the network is equal to work done from station A to station B then work done from station B to station C and then work done plus work done from station C to station D and plus work done from station D to station A.

$$W = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$

Now if we add all the work will lead to this particular equation

$$\boldsymbol{W = \mu RT_H ln\left(\frac{V_2}{V_1}\right) - \mu RT_C ln(\frac{V_3}{V_4})}$$

So, this is the Carnot cycle.

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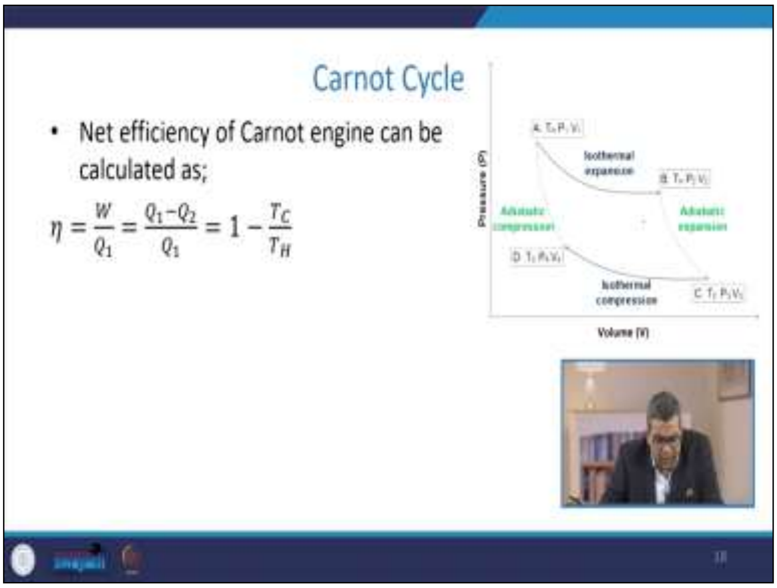

Now we are interested in calculating the net efficiency of the Carnot engine. So, you can calculate the net efficiency by

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{T_C}{T_H}$$

In this way, you can calculate the system's net efficiency with respect to this particular Carnot cycle.

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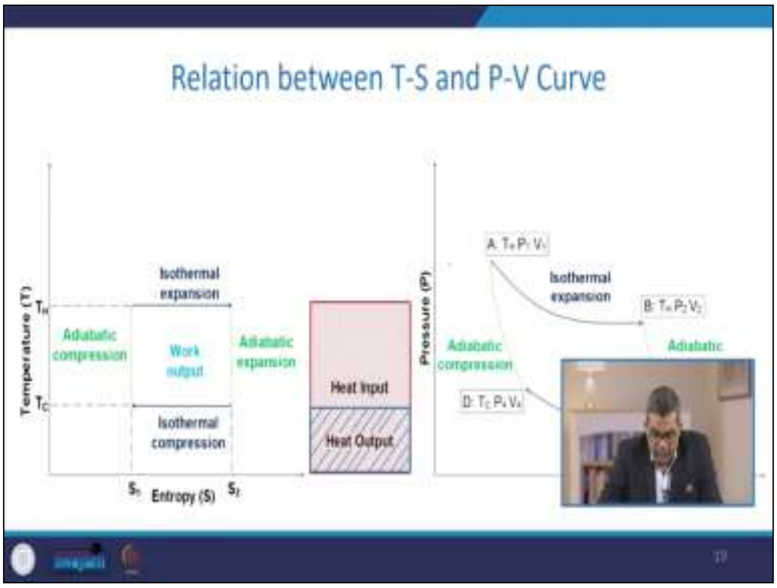

Sometimes we are interested in establishing the relationship between temperature and entropy, or pressure or volume curve. So, you can see that here, the temperature and entropy in the adiabatic compression are the work output, then isothermal compression and adiabatic compression during the adiabatic compression, the entropy remain constant. Then this is the heat input and heat output.

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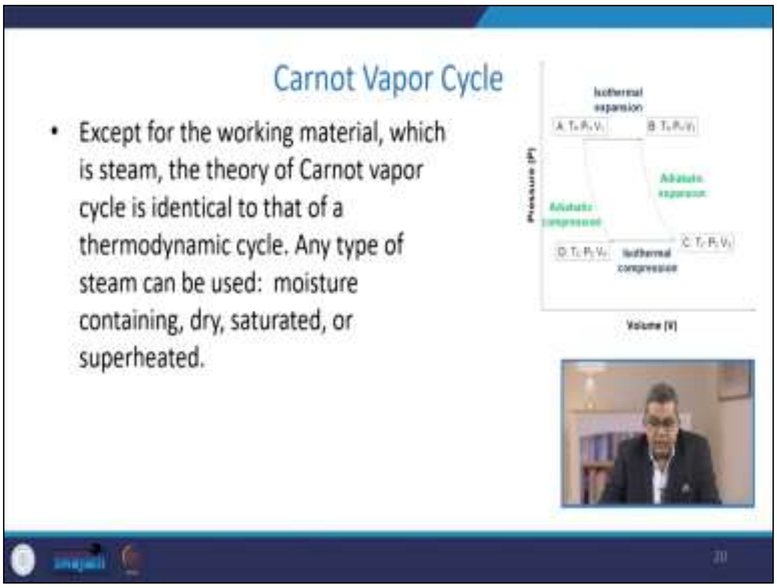

So, you can establish the relationship; similarly, we can have the Carnot vapor cycle except for the working material, which is steam. The theory of the Carnot vapor cycle is identical to that of the thermodynamic cycle. So, any type of steam can be used: moisture-containing, dry steam, saturated steam, superheated steam, and this is your Carnot vapor cycle.

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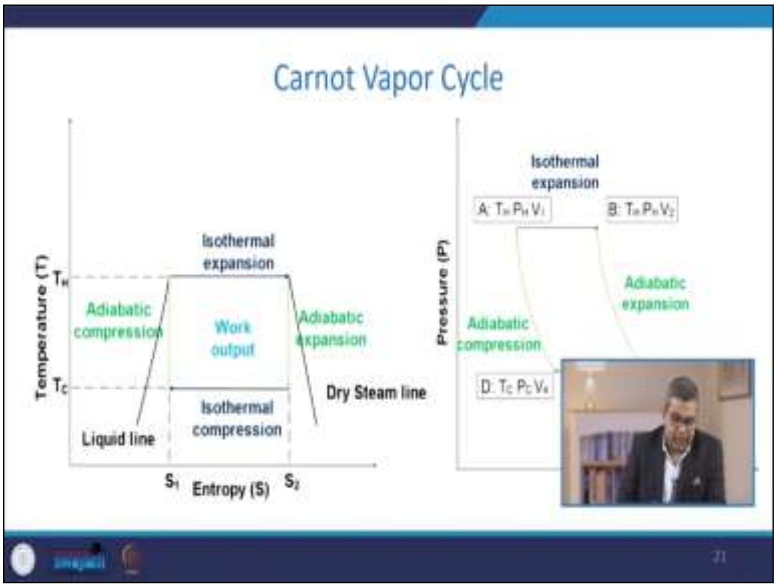

Now, here again, if we try to establish the temperature versus entropy or pressure versus temperature, you can see that here this is the adiabatic compression, and during this course of time, this is the isothermal expansion. So, whatever work is carried out over here, it goes to the adiabatic expansion, and again it goes to the isothermal compression, and the system is again regaining its value. So, you can calculate the network being carried out in this particular system.

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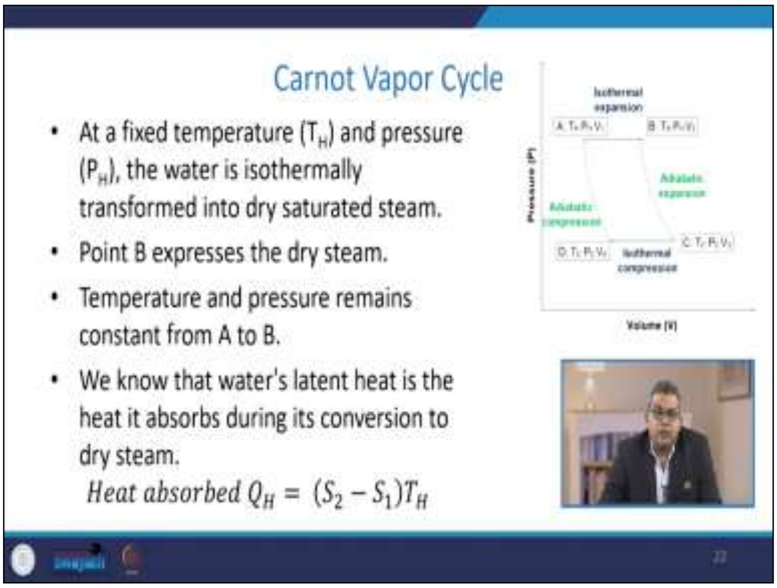

Now at a fixed temperature T H in the previous diagram, fixed temperature, and pressure, the water is isothermally transformed into dry saturated steam. Now, this point B expresses the dry steam. Now temperature and pressure remain constant from A to B. Now we know that the water's latent heat is the heat it absorbs during the conversion to dry steam. So, heat absorbed is

$$Q_H = (S_2 - S_1)T_H$$

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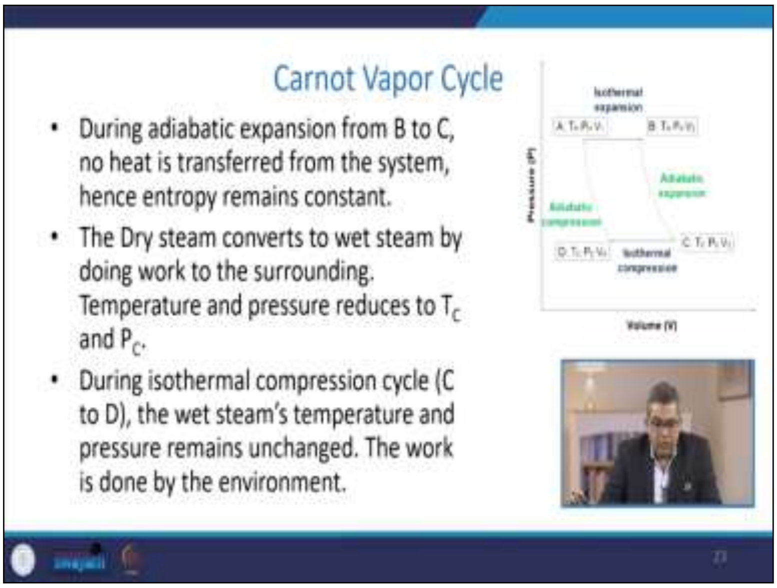

Now during the adiabatic expansion from B to C, no heat is transferred from the system therefore, entropy remains constant. Now the dry steam converts into the wet steam by doing work to the surrounding, and temperature pressure reduces to T C and P C this one. So, during the isothermal compression cycle from C to D the wet steam temperature and pressure remain unchanged, and the environment does the work.

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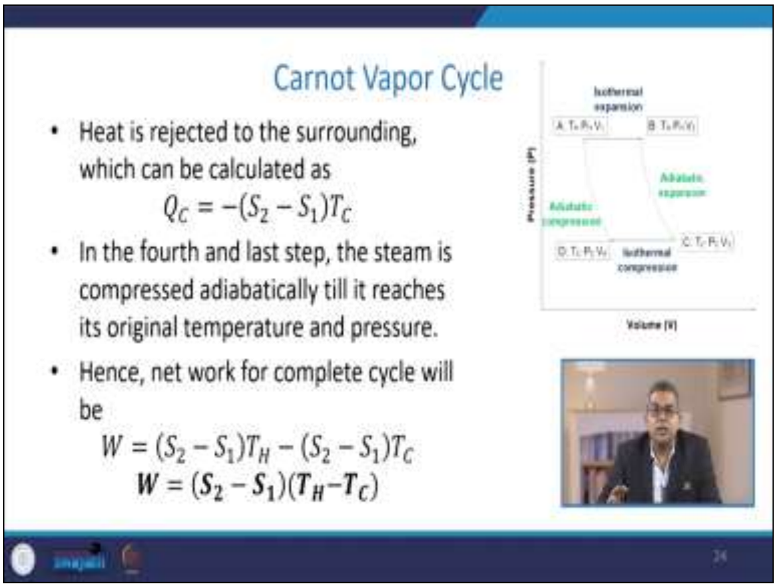

So, the heat rejected to the surrounding this can be calculated by

$$Q_C = -(S_2 - S_1)T_C$$

Now in the fourth and last step, the esteem is compressed adiabatically till it reaches its original temperature and pressure; therefore, the net-work to complete this cycle would be w is equal

$$W = (S_2 - S_1)T_H - (S_2 - S_1)T_C$$
$$\boldsymbol{W = (S_2 - S_1)(T_H - T_C)}$$

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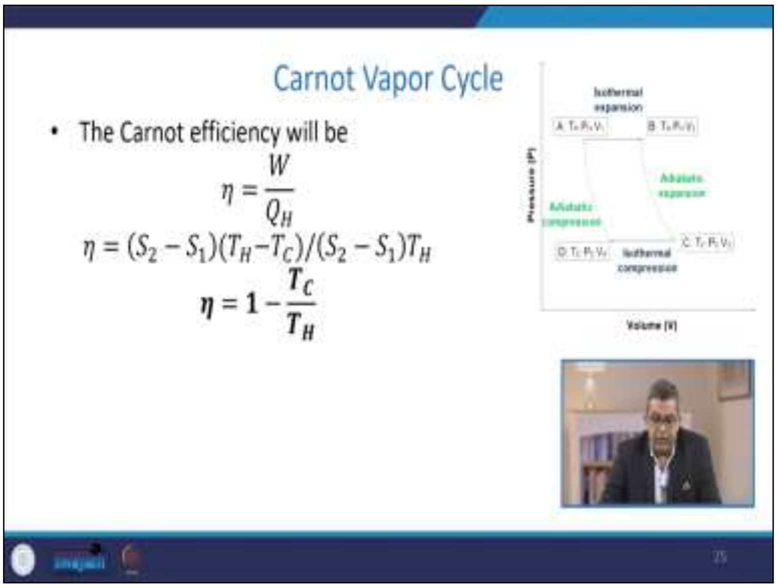

So, obviously, when we calculated this work, we were interested in Carnot's efficiency. So, the Carnot efficiency for this entire cycle would be

$$\eta = \frac{W}{Q_H}$$

$$\eta = (S_2 - S_1)(T_H - T_C)/(S_2 - S_1)T_H$$

$$\boldsymbol{\eta = 1 - \frac{T_C}{T_H}}$$

So, the Carnot efficiency for this particular cycle or Carnot vapour cycle is represented like this.

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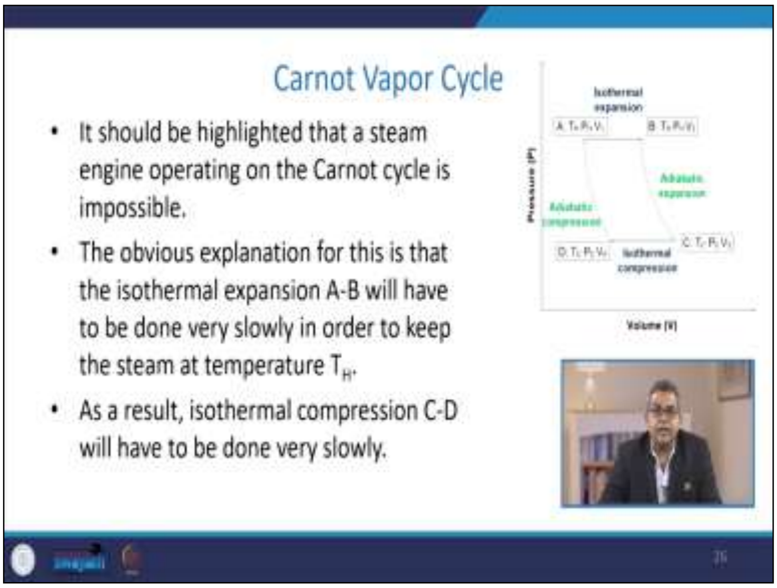

Now it should be highlighted that a steam engine operating on the Carnot cycle is impossible. The obvious explanation for this is that the isothermal expansion from A to B will have to be done very slowly in order to keep the steam temperature maintained at T H. As a result, the isothermal compression from C to D will have to be done very slowly.

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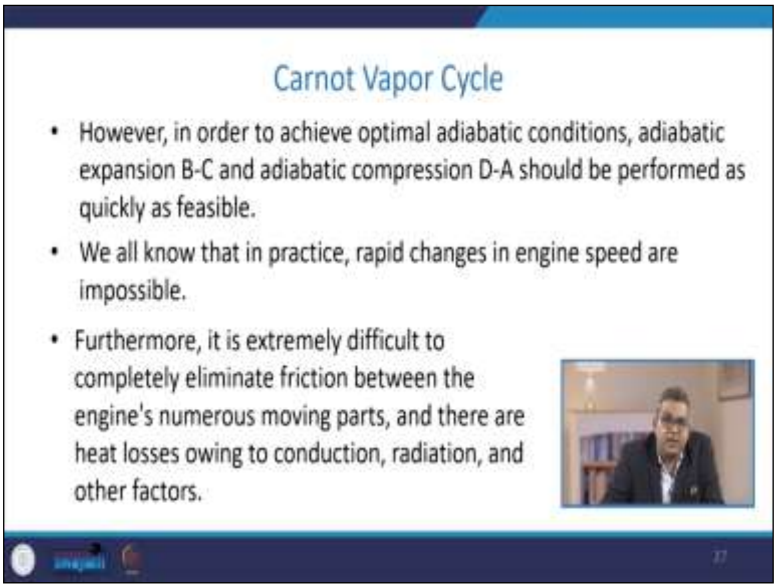

However, to achieve the optimal adiabatic condition, adiabatic expansion B to C and adiabatic compression from D to A should be performed as quickly as feasible. We know that in practice, the rapid change in engine speed are impossible practically it is impossible. So, furthermore, it is extremely difficult to completely eliminate the friction between the engines numerous moving parts and there are heat losses going to the condensing conduction radiation and other factors.

So, therefore we cannot achieve complete or efficiency or 100% efficiency. Now apart from this Carnot cycle there is another cycle which is very popular that is called the Rankine cycle.

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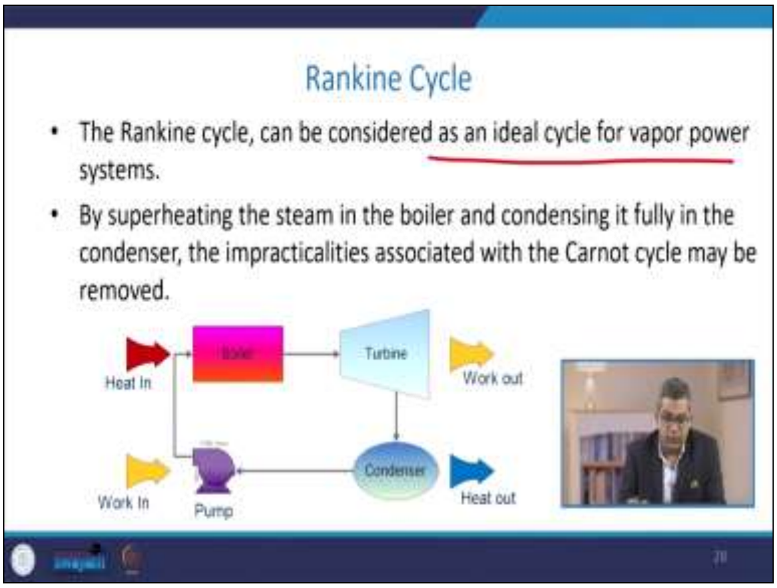

This can be considered as an ideal cycle for the vapor power system we discussed this vapor power system in the previous one. By superheating the steam in the boiler and condensing it fully in the condenser, the impracticality associated with the Carnot cycle may be removed. So, you can say that this cycle tries to overcome certain of deficiencies of the Carnot cycle.

Now here is the conceptual diagram that is heated in the boiler, then it performs some work in the turbine that is the workout, then the steam will get condensed. So, that the remaining heat you can extract it and again whatever condensate is you can pump it with the application of work to the boiler. This is a simplified diagram of this Rankine cycle. Now it works in a nutshell you can say that it works by converting water into a steam in a boiler that expands through the turbine to produce useful work.

It converts the heat into mechanical energy, which can be further transferred to the electricity by using the associated utilities.

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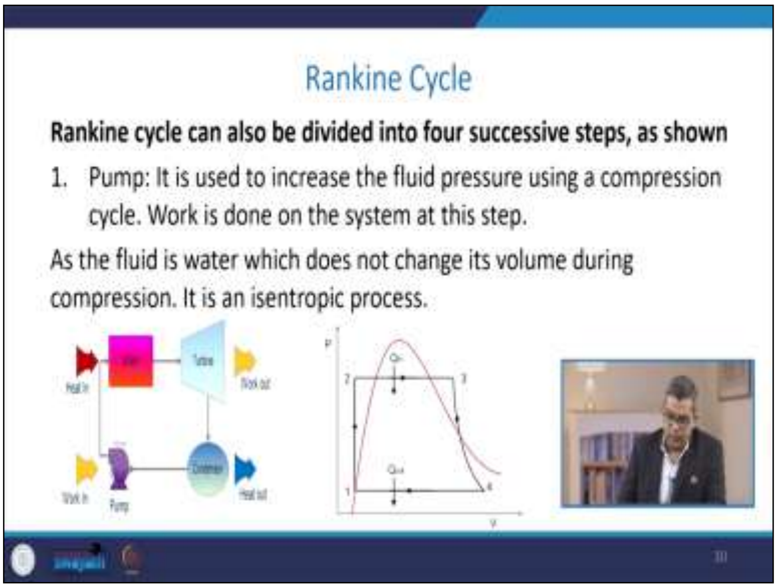

Now Rankine cycle can also be divided into four successive steps: the pumping used to increase the fluid pressure using the compression cycle. Now work is done on the system at this step. Now, as the fluid is water, it does not change its volume during the compression (incompressible), which is an isentropic process. So, you can draw the PV diagram accordingly.

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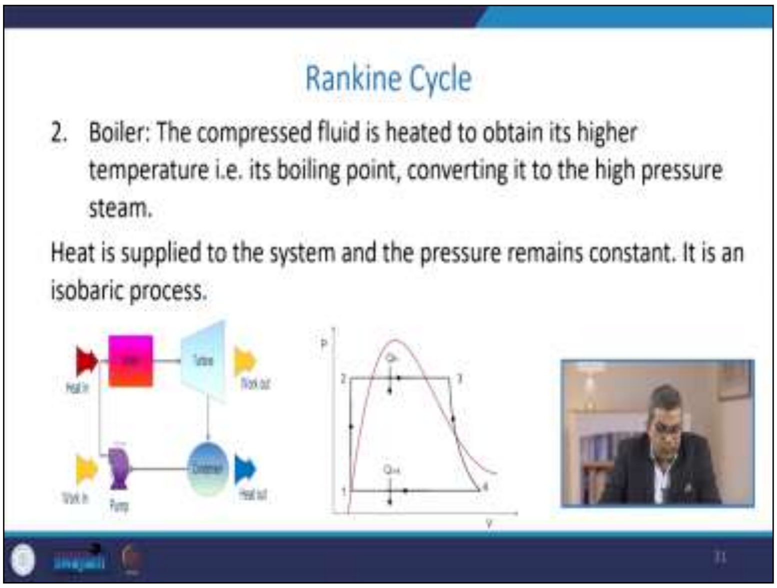

Now second is the boiler; the compressed fluid is heated to obtain its higher temperature, that is, boiling point converting it into high-pressure steam. So, heat is supplied to the system, and the pressure remains constant; it is an isobaric process.

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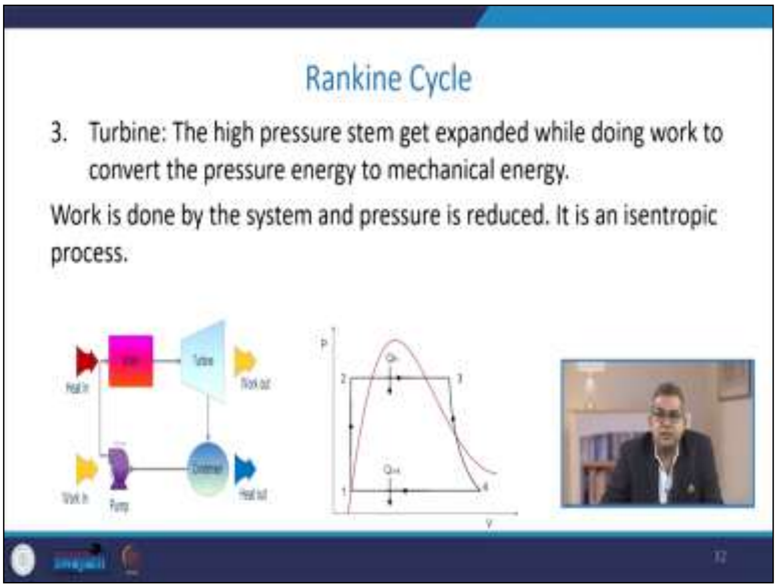

The third one is the turbine; the high-pressure steam gets expanded while working on converting the pressure energy into mechanical work. So, work is done by the system, and pressure is reduced. So, this is an isentropic process you can visualize this in this figure.

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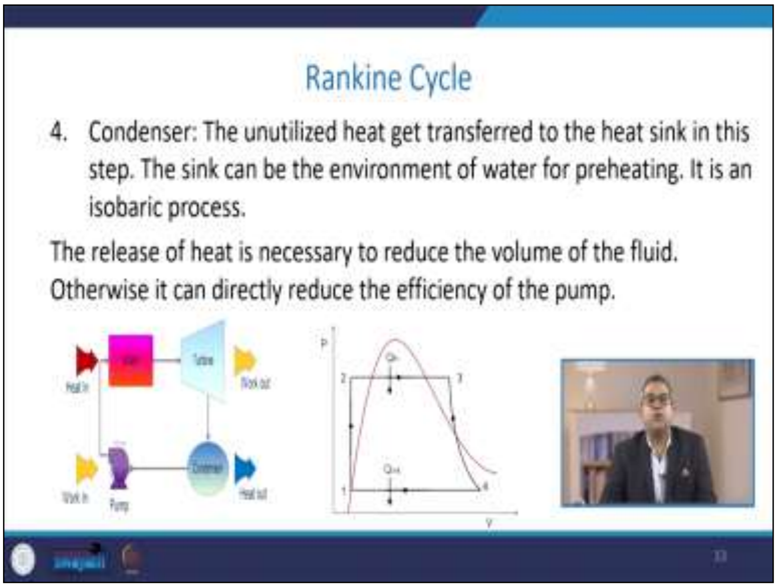

Now condensing, the unutilized heat gets transferred to the heat sinks in this step, and the sink can be an environment of water for preheating or some other process; it is an isobaric process. So, the release of heat is necessary to reduce the volume of fluid. Otherwise, it can directly reduce the efficiency of this pump. So, this is again quite an essential aspect of the process.

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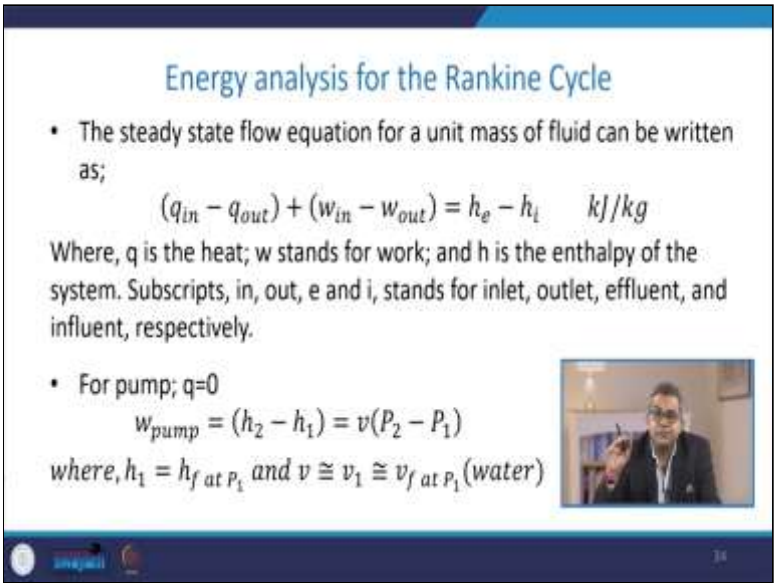

Now the study state flow equation for unit mass of fluid this can be written as

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \qquad kJ/kg$$

Where, q is the heat; w stands for work; and h is the enthalpy of the system. Subscripts, in, out, e and i, stands for inlet, outlet, effluent, and influent, respectively.

- For pump; q=0

$$w_{pump} = (h_2 - h_1) = v(P_2 - P_1)$$

$where,\ h_1 = h_{f\ at\ P_1}\ and\ v \cong v_1 \cong v_{f\ at\ P_1}(water)$

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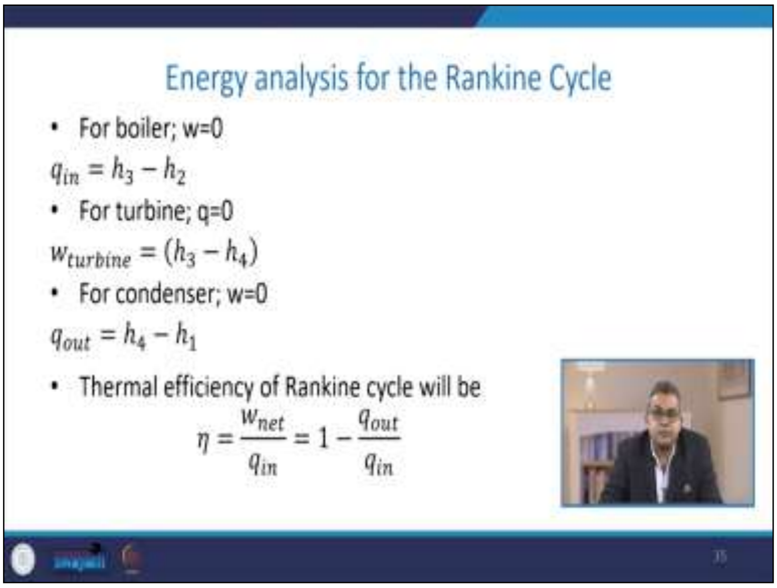

- For boiler; w=0

$q_{in} = h_3 - h_2$

- For turbine; q=0

$w_{turbine} = (h_3 - h_4)$

- For condenser; w=0

$q_{out} = h_4 - h_1$

- Thermal efficiency of Rankine cycle will be

$$\eta = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

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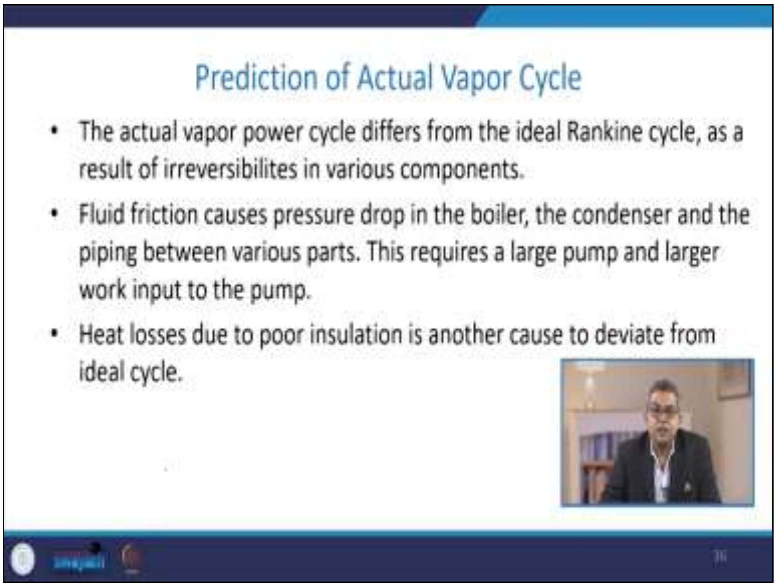

Now let us have a look at the prediction of the actual vapor cycle. The actual vapor cycle differs from the ideal Rankine cycle because you need to incorporate certain irreversibilities associated with the system. So, as a result of reversibility in the various components, we have to look into the concept of the actual vapor cycle. Now flute friction sometimes causes the pressure drop in the boiler, the condenser, and the piping network between the various parts. Now, this requires a large pump and a large work input to the pump.

So, sometimes you may experience heat losses attributed to poor insulation; this is again one of the causes to deviate from the ideal cycle. So, various things are attributed to the deviation from the ideal cycle. So, that is why we are always looking for the actual vapor cycle.

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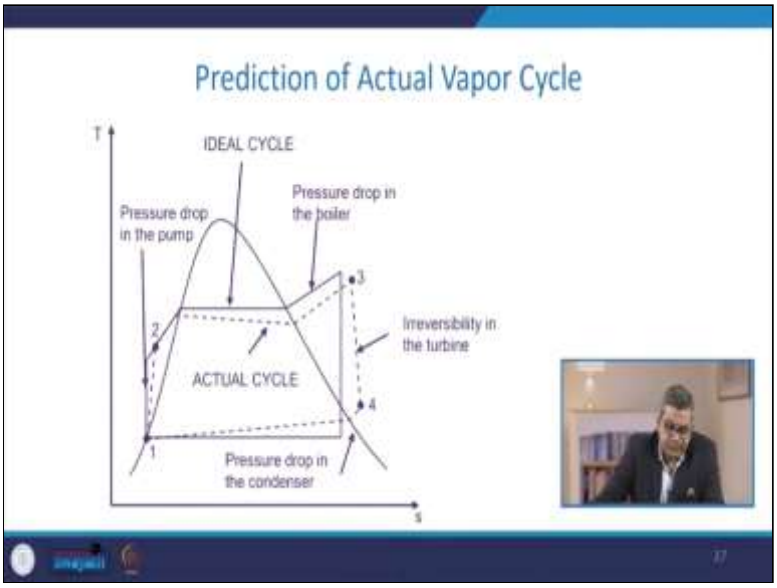

Now here you see that we have one ideal cycle, this one, and of course, keeping because of all irreversibilities and other things, we have the actual cycle. So, from an engineering perspective, we are always looking for this kind of deviation from the ideal behavior. So, this may be attributed to the irreversibilities in the turbine.

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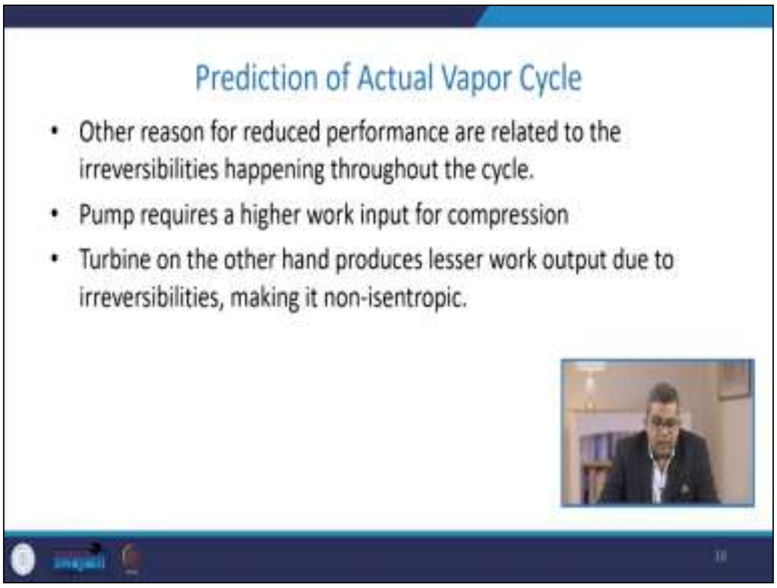

The other reason for the reduced performance is attributed to the irreversibilities happening throughout the cycle, not to the individual component. To overcome such a things pump requires a higher work input for the compression. On the other hand, turbine produces a lesser work output due to its inherent irreversibilities, making it nonisentropic.

So, we have to look into these variables in these verticals while considering the actual vapor cycle into consideration. Now the question arises about the improvisation of efficiency of the actual vapor cycle.

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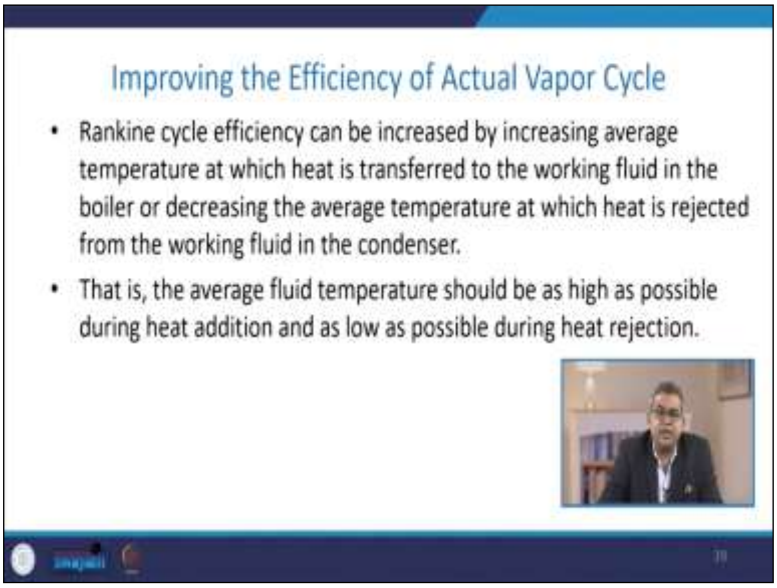

Rankine cycle efficiency can be increased by increasing the average temperature at which the heat is transferred to the boiler's working fluid or decreasing the average temperature at which heat is rejected from the working fluid in the condenser. So that is, the average fluid temperature should be as high as possible during heat addition and as low as possible during the heat rejection.

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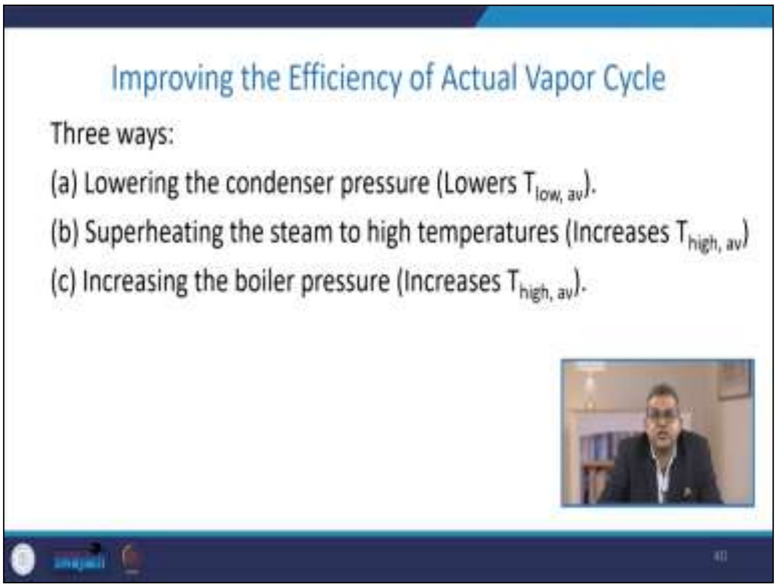

There are three ways to carry out this one; one is that lowering the condenser pressure lowers the average temperature. Superheating the steam to a high temperature that increases the T high or increasing the boiler pressure that means T high you need to have this temperature on the higher side. Now, this is related to your actual vapor cycle prediction.

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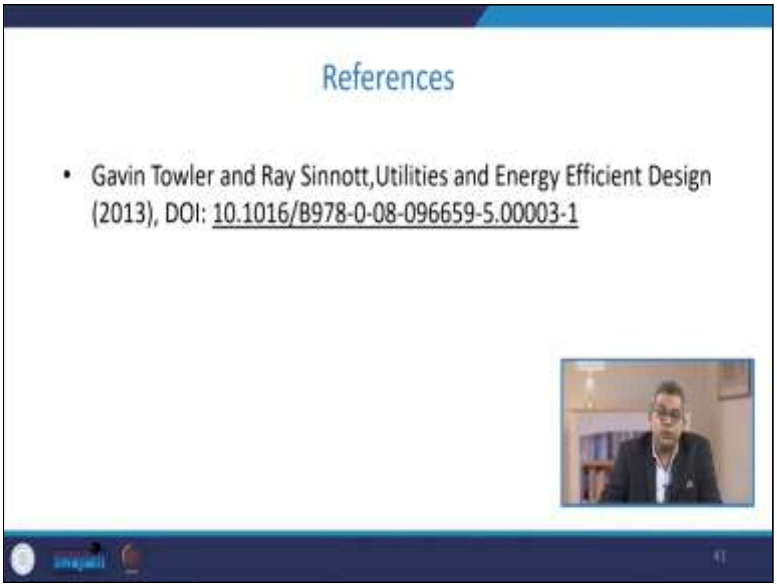

Now by this way we are coming to the end of this particular lecture and again if you are looking for more knowledge there is one difference which is attached to this particular slide, thank you very much.