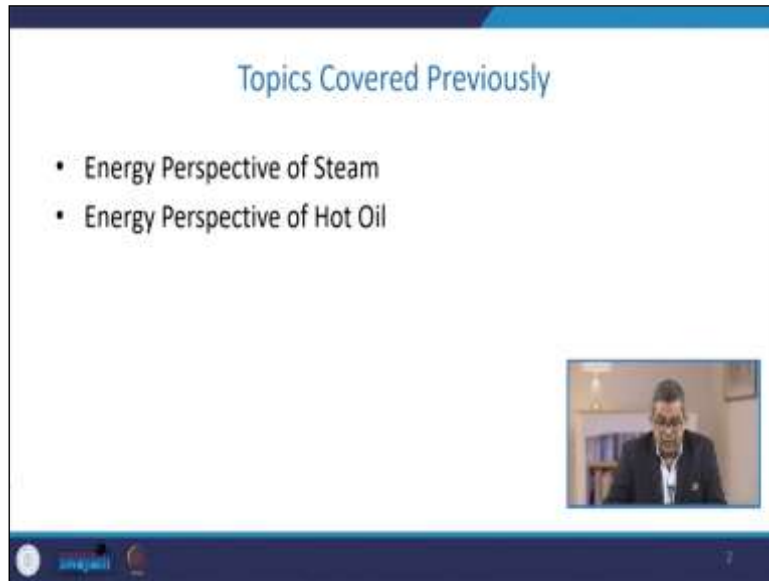


**Chemical Process Utilities**  
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**Lecture – 3**  
**Power Cycle**

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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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**Introduction**

- Engines are the thermodynamic system used to generate a net power output. The produced power can be used in variety of applications, which can be termed as work done by the system.
- On the other hand, some devices are used to extract heat from the colder environment and deliver it to the hotter environment. These are termed as refrigerator, heat pump, or air conditioner.
- The natural tendency of heat is to flow from hotter medium to the colder medium. Hence, in the second case external work needs to be done for heat transfer.



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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### Introduction

- However, both systems work on a principal of thermodynamic cycles.
- Depending upon the type of work, these cycles can be classified into two categories viz.
  - Power Cycles
  - Refrigeration cycles
- In terms of working fluid, these cycles can be termed as;
  - Gas cycles
  - Vapor cycles




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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### Introduction

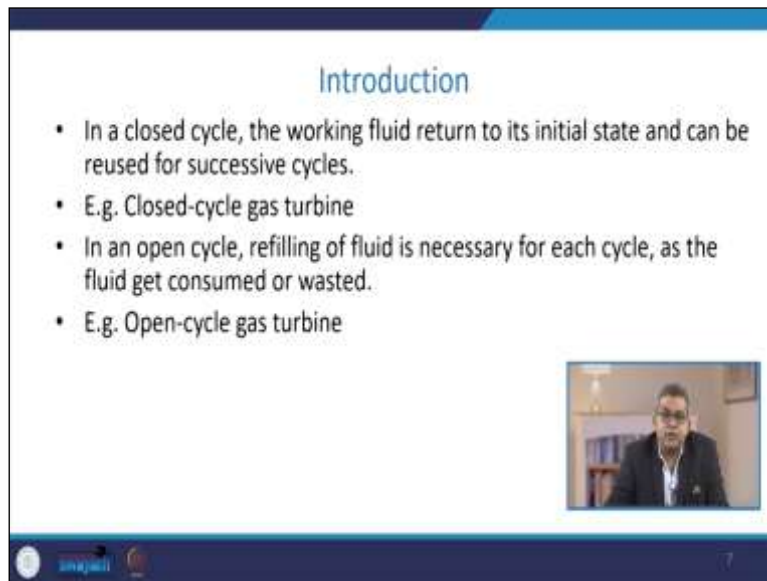
- In gas cycles, the working fluid as gas does not change its physical state throughout the heat transfer cycle. E.g. Helium
- In vapor cycle, the working fluid remains in liquid phase in one half of the cycle and in gaseous phase on the other half. E.g. Steam
- In terms of system used, these thermodynamic cycles are termed as;
  - Closed cycles
  - Open cycles



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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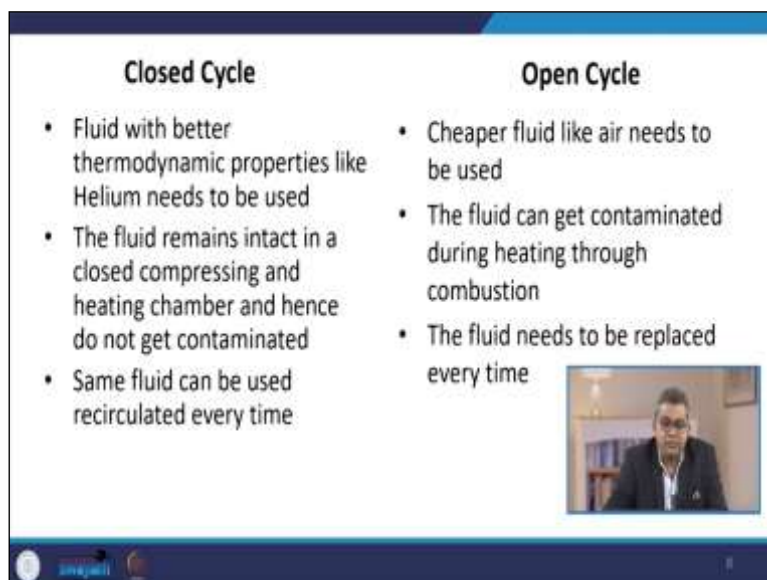
**Introduction**

- In a closed cycle, the working fluid return to its initial state and can be reused for successive cycles.
- E.g. Closed-cycle gas turbine
- In an open cycle, refilling of fluid is necessary for each cycle, as the fluid get consumed or wasted.
- E.g. Open-cycle gas turbine




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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<b>Closed Cycle</b>	<b>Open Cycle</b>
<ul style="list-style-type: none"><li>• Fluid with better thermodynamic properties like Helium needs to be used</li><li>• The fluid remains intact in a closed compressing and heating chamber and hence do not get contaminated</li><li>• Same fluid can be used recirculated every time</li></ul>	<ul style="list-style-type: none"><li>• Cheaper fluid like air needs to be used</li><li>• The fluid can get contaminated during heating through combustion</li><li>• The fluid needs to be replaced every time</li></ul>



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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Closed Cycle	Open Cycle
<ul style="list-style-type: none"><li>• Fluid does not affect the life cycle of system. E.g. wear of turbine blades</li><li>• Preferable for stationary installation and marine uses</li><li>• High maintenance and installation cost</li></ul>	<ul style="list-style-type: none"><li>• Contaminated fluid can affect the service life of the system</li><li>• Best suited for moving installation</li><li>• Low maintenance and installation cost</li></ul>

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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## Ideal Cycles

**Assumptions**

- The cycle runs smooth and does not involve any frictional losses
- Sufficient time is provided throughout the cycle. The system runs in a quasi-equilibrium during the expansion and compression cycles.
- No heat transfer and pressure loss to the surrounding, as the piping and joints are well insulated.




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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## Ideal Cycles

- Considering all of these assumptions we can establish an ideal cycle, which can help to understand the mechanism involved in the real cycle.
- The thermal efficiency ( $\eta_{Th}$ ) of a heat engine can be defined as
 
$$\eta_{Th} = \frac{W_{net}}{Q_{in}}$$
- $W_{net}$  = Net work done by the system
- $Q_{in}$  = Heat input to the system



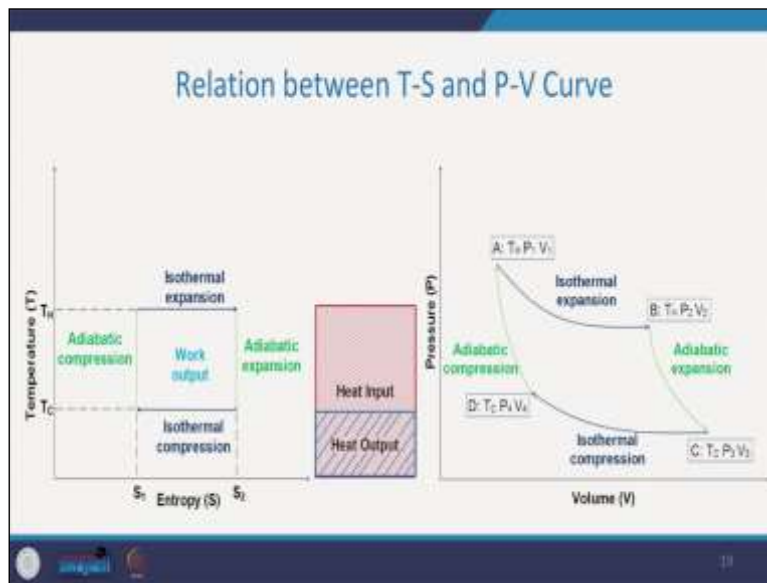
Considering all these assumptions, we can establish an ideal cycle that can help us understand the mechanism involved in the real cycle. Sometimes we are very much

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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### Carnot Cycle

- The Carnot cycle was proposed by Lenard Carnot.
- It gives a thermodynamic interpretation of the maximum possible efficiency that could be obtained from a heat engine.
- The Carnot cycle is an ideal reversible closed thermodynamic cycle, which can be divided into four successive operations

The diagram shows a P-V plot with Pressure (P) on the vertical axis and Volume (V) on the horizontal axis. The cycle consists of four states: A (T<sub>H</sub>, P<sub>H</sub>, V<sub>1</sub>), B (T<sub>H</sub>, P<sub>B</sub>, V<sub>2</sub>), C (T<sub>L</sub>, P<sub>C</sub>, V<sub>2</sub>), and D (T<sub>L</sub>, P<sub>D</sub>, V<sub>1</sub>). The processes are: A to B (isothermal expansion), B to C (adiabatic expansion), C to D (isothermal compression), and D to A (adiabatic compression).

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<sub>H</sub> leading to an isothermal expansion. So, this is this is the pressure and volume.

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### Carnot Cycle

1. Isothermal heat addition from heat reservoir at (T<sub>H</sub>), leading to an isothermal expansion

- The heat is absorbed by the system (gas) and the net work is done by the gas to the surrounding. The work can be calculated as

$$W_{A-B} = Q_H = \mu RT_H \ln\left(\frac{V_2}{V_1}\right)$$

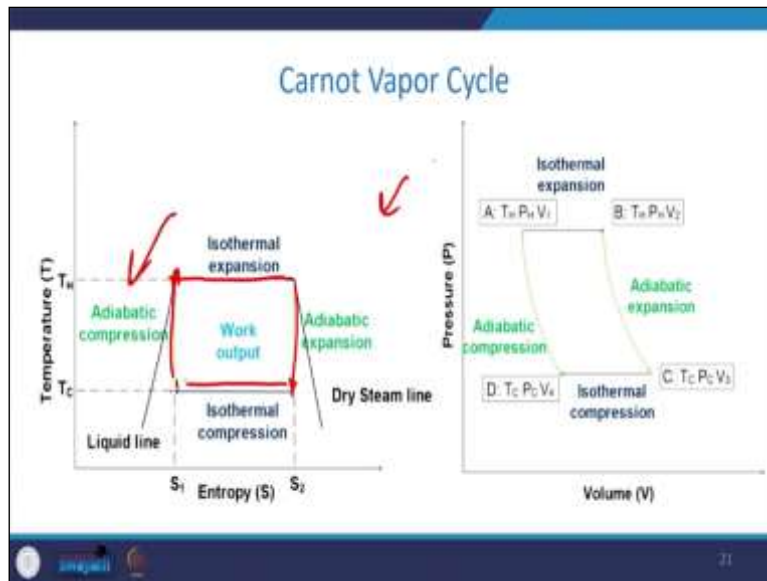
The diagram is similar to the previous one, but with a red arrow pointing from state A to state B, indicating the isothermal expansion process. The vertical axis is labeled 'P' and the horizontal axis is labeled 'V'.

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,

$$W_{A-B} = Q_H = \mu RT_H \ln\left(\frac{V_2}{V_1}\right)$$

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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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### Carnot Cycle

2. Isentropic expansion from higher temperature ( $T_H$ ) to lower temperature ( $T_C$ ), leading to an adiabatic expansion.
  - The system is thermodynamically insulated
  - The work is done by the system on the surrounding. It can be calculated as;

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

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,

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

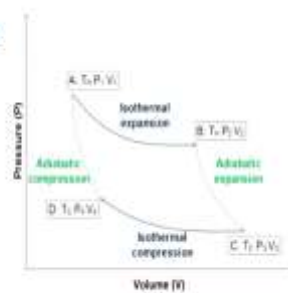
Now I told you that usual thermodynamic law they are prevailing. So, this is an isentropic expansion. So, we are using this mathematical formula.

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**Carnot Cycle**

3. Isothermal heat rejection to low temperature at heat sink, leading to isothermal compression.

- The heat is lost to the surrounding during this step
- The work is done on the system (negative work) by the surrounding. It can be calculated as;

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


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

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

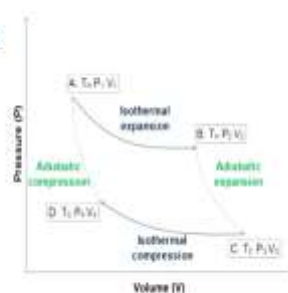
Now this is the final volume for this step and this is the initial volume.

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**Carnot Cycle**

4. Isentropic compression from low temperature to high temperature, leading to the adiabatic compression.

- The system is again considered thermally insulated and the gas continue to compress to achieve the original high temperature  $T_H$ .
- The work is done on the system

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


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

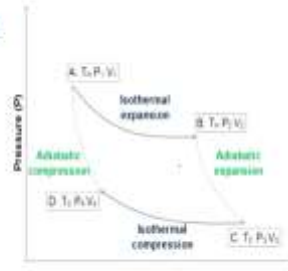

$$W = \mu RT_H \ln\left(\frac{V_2}{V_1}\right) - \mu RT_C \ln\left(\frac{V_3}{V_4}\right)$$

So, this is the Carnot cycle.

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### Carnot Cycle

- Net efficiency of Carnot engine can be calculated as;

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



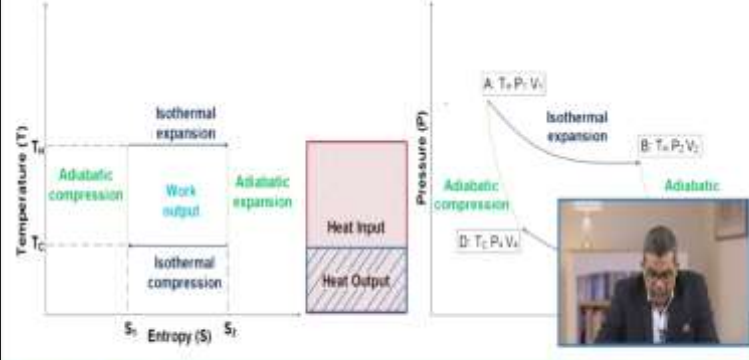

Now we are interested in calculating the net efficiency of the Carnot engine. So, you can calculate the net efficiency by

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

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

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### Relation between T-S and P-V Curve

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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### Carnot Vapor Cycle

- Except for the working material, which is steam, the theory of Carnot vapor cycle is identical to that of a thermodynamic cycle. Any type of steam can be used: moisture containing, dry, saturated, or superheated.

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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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### 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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### Carnot Vapor Cycle

- At a fixed temperature ( $T_H$ ) and pressure ( $P_H$ ), the water is isothermally transformed into dry saturated steam.
- Point B expresses the dry steam.
- Temperature and pressure remains constant from A to B.
- We know that water's latent heat is the heat it absorbs during its conversion to dry steam.  
Heat absorbed  $Q_H = (S_2 - S_1)T_H$

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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### Carnot Vapor Cycle

- During adiabatic expansion from B to C, no heat is transferred from the system, hence entropy remains constant.
- The Dry steam converts to wet steam by doing work to the surrounding. Temperature and pressure reduces to  $T_C$  and  $P_C$ .
- During isothermal compression cycle (C to D), the wet steam's temperature and pressure remains unchanged. The work is done by the environment.

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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### Carnot Vapor Cycle

- Heat is rejected to the surrounding, which can be calculated as
 
$$Q_C = -(S_2 - S_1)T_C$$
- In the fourth and last step, the steam is compressed adiabatically till it reaches its original temperature and pressure.
- Hence, net work for complete cycle will be
 
$$W = (S_2 - S_1)T_H - (S_2 - S_1)T_C$$

$$W = (S_2 - S_1)(T_H - T_C)$$

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 steam is compressed adiabatically till it reaches its original temperature and pressure; therefore, the net-work to complete this cycle would be  $w$  is equal

$$W = (S_2 - S_1)T_H - (S_2 - S_1)T_C$$

$$W = (S_2 - S_1)(T_H - T_C)$$

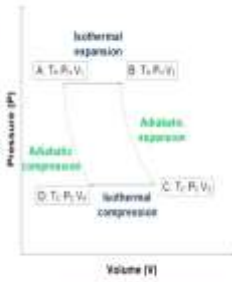

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### Carnot Vapor Cycle

- The Carnot efficiency will be
 
$$\eta = \frac{W}{Q_H}$$

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

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

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

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

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

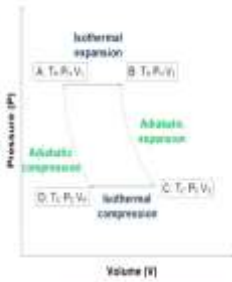

$$\eta = 1 - \frac{T_C}{T_H}$$

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

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### Carnot Vapor Cycle

- 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 A-B will have to be done very slowly in order to keep the steam at temperature  $T_H$ .
- As a result, isothermal compression C-D will have to be done very slowly.

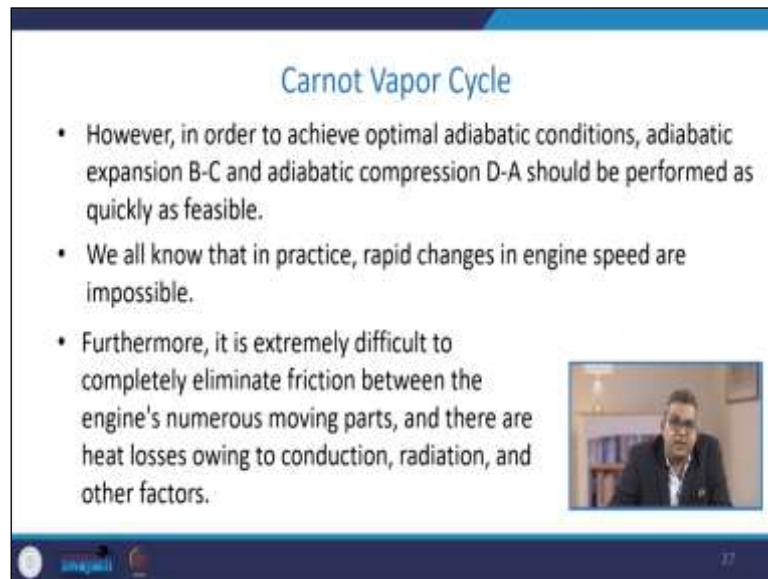



Now it should be highlighted that a steam engine operating on the Carnot cycle is impossible. The obvious explanation for this is that the isothermal expansion from A to B



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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**Carnot Vapor Cycle**

- However, in order to achieve optimal adiabatic conditions, adiabatic expansion B-C and adiabatic compression D-A should be performed as quickly as feasible.
- We all know that in practice, rapid changes in engine speed are impossible.
- Furthermore, it is extremely difficult to completely eliminate friction between the engine's numerous moving parts, and there are heat losses owing to conduction, radiation, and other factors.

The slide includes a small video inset of a man in a suit speaking, and a footer with a logo and the number 77.

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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### Rankine Cycle

- The Rankine cycle, can be considered as an ideal cycle for vapor power systems.
- By superheating the steam in the boiler and condensing it fully in the condenser, the impracticalities associated with the Carnot cycle may be removed.

The diagram illustrates the Rankine cycle with four main components: a boiler (pink rectangle), a turbine (light blue trapezoid), a condenser (green circle), and a pump (purple circle). A red arrow labeled 'Heat In' points into the boiler. A yellow arrow labeled 'Work In' points into the pump. A yellow arrow labeled 'Work out' points away from the turbine. A blue arrow labeled 'Heat out' points away from the condenser. The components are connected in a clockwise cycle: boiler to turbine, turbine to condenser, condenser to pump, and pump back to boiler. A small video inset in the bottom right corner shows a man in a suit speaking.

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.

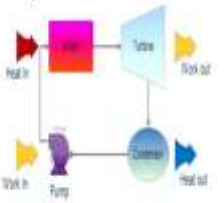
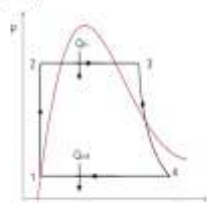

It converts the heat into mechanical energy, which can be further transferred to the electricity by using the associated utilities.

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### Rankine Cycle

**Rankine cycle can also be divided into four successive steps, as shown**

- 1. Pump:** It is used to increase the fluid pressure using a compression cycle. Work is done on the system at this step.  
As the fluid is water which does not change its volume during compression. It is an isentropic process.

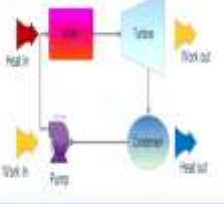
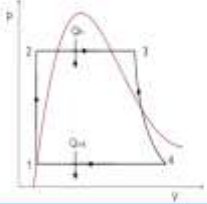





Now Rankine cycle can also be divided into four successive steps: the pumping used to increase the fluid pressure using the compression cycle. Now work is done on the system at this step. Now, as the fluid is water, it does not change its volume during the compression (incompressible), which is an isentropic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

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### Rankine Cycle

- 2. Boiler:** The compressed fluid is heated to obtain its higher temperature i.e. its boiling point, converting it to the high pressure steam.  
Heat is supplied to the system and the pressure remains constant. It is an isobaric process.

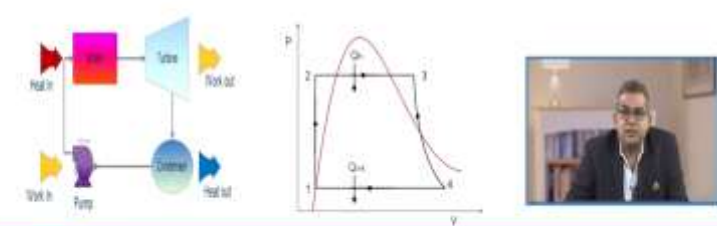




Now second is the boiler; the compressed fluid is heated to obtain its higher temperature, that is, boiling point converting it into high-pressure steam. So, heat is supplied to the system, and the pressure remains constant; it is an isobaric process.

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### Rankine Cycle

3. Turbine: The high pressure steam get expanded while doing work to convert the pressure energy to mechanical energy.  
Work is done by the system and pressure is reduced. It is an isentropic process.



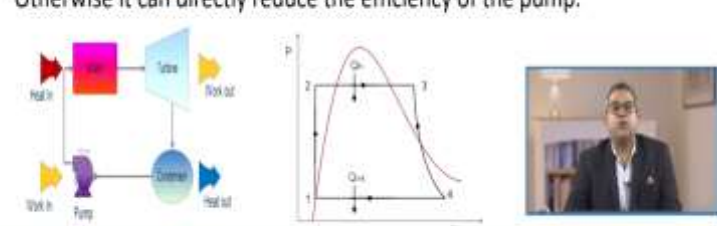
The diagram shows a schematic of the Rankine cycle components: a boiler (red) receiving heat input, a turbine (light blue) producing work output, a condenser (green) receiving heat output, and a pump (purple) receiving work input. To the right is a P-v diagram showing the expansion process from state 2 to state 3, which is an isentropic expansion. The area under the curve from 2 to 3 represents the work done by the turbine. A small video inset of the presenter is visible in the bottom right corner.

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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### Rankine Cycle

4. Condenser: The unutilized heat get transferred to the heat sink in this step. The sink can be the environment of water for preheating. It is an isobaric process.  
The release of heat is necessary to reduce the volume of the fluid. Otherwise it can directly reduce the efficiency of the pump.



The diagram shows the same Rankine cycle schematic as above. The P-v diagram highlights the condensation process from state 3 to state 4, which is an isobaric process. The area under the curve from 3 to 4 represents the heat rejected to the condenser. A small video inset of the presenter is visible in the bottom right corner.

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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### Energy analysis for the Rankine Cycle

- The steady state flow equation for a unit mass of fluid can be written as;
 
$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad kJ/kg$$

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,  $h_1 = h_f \text{ at } P_1$  and  $v \cong v_1 \cong v_f \text{ at } P_1 \text{ (water)}$



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

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

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,  $h_1 = h_f \text{ at } P_1$  and  $v \cong v_1 \cong v_f \text{ at } P_1 \text{ (water)}$

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### Energy analysis for the Rankine Cycle

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



- 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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**Prediction of Actual Vapor Cycle**

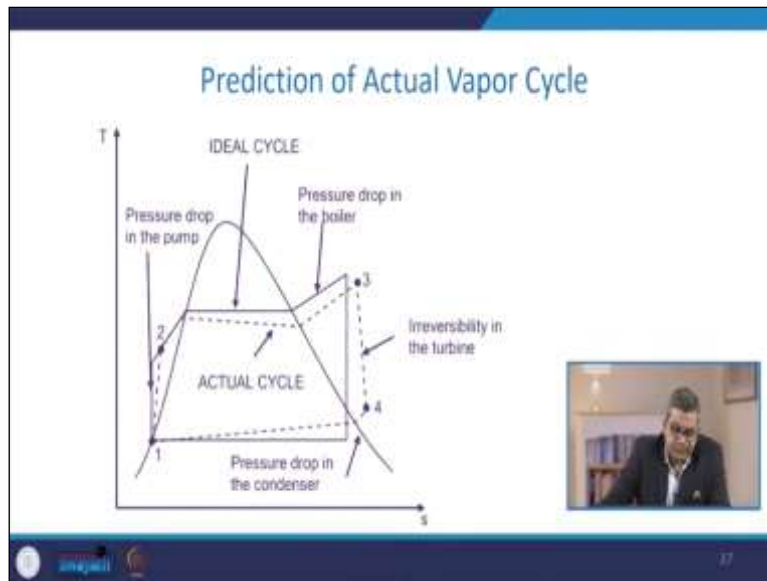
- The actual vapor power cycle differs from the ideal Rankine cycle, as a result of irreversibilities in various components.
- Fluid friction causes pressure drop in the boiler, the condenser and the piping between various parts. This requires a large pump and larger work input to the pump.
- Heat losses due to poor insulation is another cause to deviate from ideal cycle.

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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 fluid 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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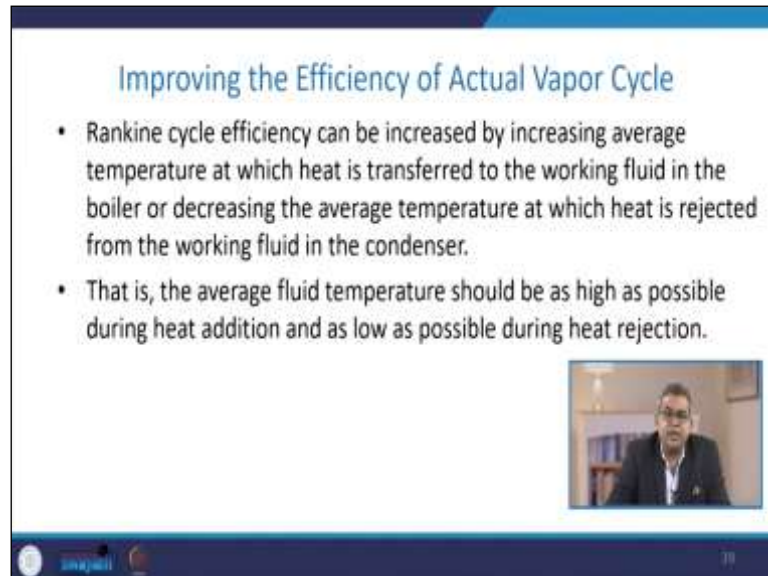
### Prediction of Actual Vapor Cycle

- Other reason for reduced performance are related to the irreversibilities happening throughout the cycle.
- Pump requires a higher work input for compression
- Turbine on the other hand produces lesser work output due to irreversibilities, making it non-isentropic.

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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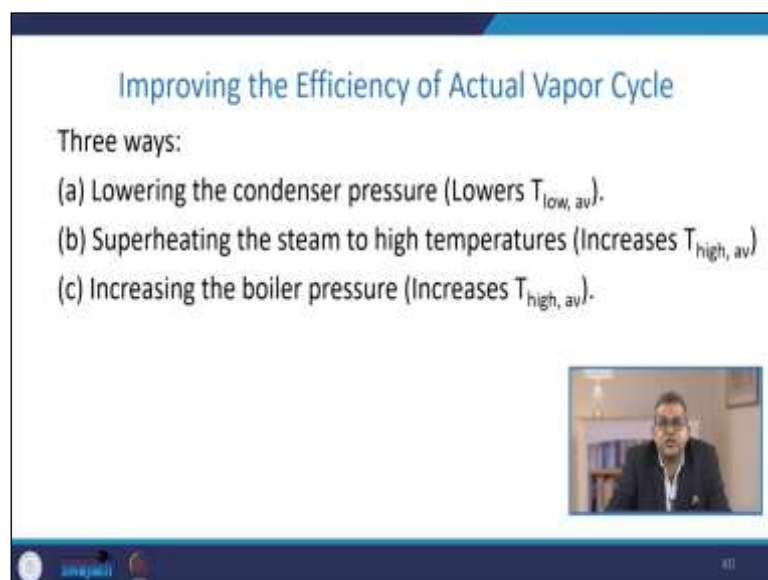
**Improving the Efficiency of Actual Vapor Cycle**

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

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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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**Improving the Efficiency of Actual Vapor Cycle**

Three ways:

- (a) Lowering the condenser pressure (Lowers  $T_{low, av}$ ).
- (b) Superheating the steam to high temperatures (Increases  $T_{high, av}$ ).
- (c) Increasing the boiler pressure (Increases  $T_{high, av}$ ).

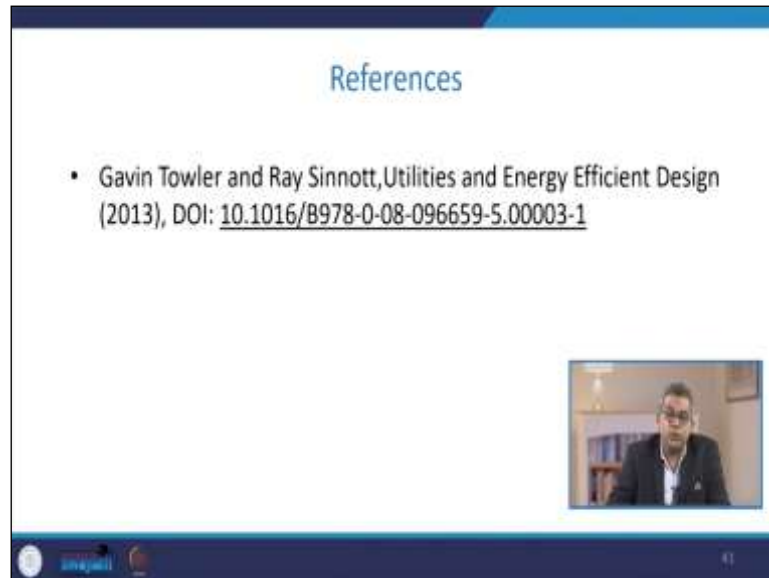
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There are three ways to carry out this one; one is that lowering the condenser pressure lowers the average temperature. Superheating the steam to a high temperature that



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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References

- Gavin Towler and Ray Sinnott, Utilities and Energy Efficient Design (2013), DOI: [10.1016/B978-0-08-096659-5.00003-1](https://doi.org/10.1016/B978-0-08-096659-5.00003-1)

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.