Basics of Mechanical Engineering-3

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Week 04

Lecture 15: Vapour Power Cycles

Well, friends, I am sure you are enjoying this course. While going through the lectures, I have also given some examples. Dr. Amandeep Singh is also dealing with some of the problems which are related to the lecture we have covered. In the examination, we will try to have a maximum of two-mark problems. So, if it is a two-mark problem, there will be one step or two steps.

The magnitude for every term will be given in the examination. The units are something you should try to keep in your mind. So, when we give the problem, there can be a mismatch in the units. So, you have to normalize and then try to solve, okay? So, now getting into the new lecture, it is going to be on the Vapour Power Cycle.

When we talk about vapour, we always try to talk about steam. Why so? Because, friends, you saw in the previous lectures, we have dealt with thermodynamic property tables. So, it is a huge table. Generation of so much data is going to be very difficult for all fluids.

So, people have picked up a few of the working fluids and then they have given the table. In our case, since it is a basic fundamental course, we will always keep it with respect to water. So now, we will try to see the Steam-Based Vapour Power Cycle. So, a cycle means there are processes like pumping, expansion, and compression. All those things will come. Power is what is generated out of the cycle will be power.

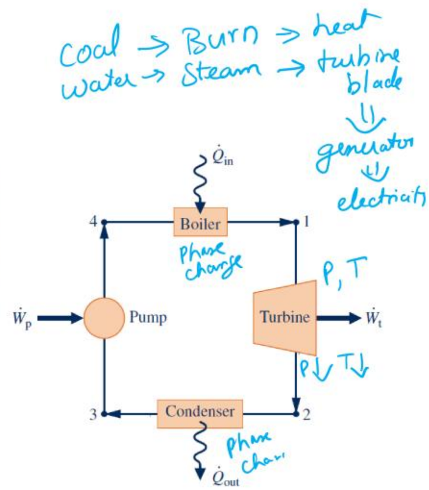
Contents

- Vapour Power Cycles
- Carnot Vapour Power Cycles
- Rankine Cycle
- Modified Rankine Cycle
- Binary Vapour Power Cycles
- Ideal Jet-Propulsion Cycle

The content of this lecture is going to be the Vapour Power Cycle. Then, we are going to go through the Carnot Vapour Power Cycle. Then, we will try to see the Rankine Cycle. Then, the Modified Rankine Cycle. Then, the Binary Vapour Power Cycle. Binary means two. Binary Vapour Power Cycle. Then, the Ideal Jet-Propulsion Cycle, which is used in planes.

Vapour Power Cycles

- Vapour power cycles form the fundamental basis of thermodynamic analysis of steam power plants, widely used in electricity generation and industrial processes.
- These cycles operate on the principle of phase change—typically involving the vapourization and condensation of a working fluid, such as water—which allows for efficient energy transfer and high thermal efficiency.
- Their primary objective is to convert thermal energy derived from fuel combustion or other heat sources into mechanical work, which can then be transformed into electrical energy.



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The Vapour Power Cycle forms the fundamental basis of thermodynamic analysis of steam power plants widely used to generate electrical energy and industrial processes.

So what happens exactly here is people start with coal, they burn coal. When you burn coal, they will try to heat water. From the water, it generates steam. From the steam, it is try to hit against a turbine blade or a turbine. From the turbine blade, we try to connect it with a generator. And from the generator we try to generate electricity. So this is how it goes. So we always call it as a thermal power plant.

Thermal power plant we try to use either directly gas and other things or boil water convert into steam and then try to use it. This cycle operates on the principle of phase change. So water converted into steam. So typically involving vaporization as a process. When you convert a liquid to a gas, so it is called as vaporization.

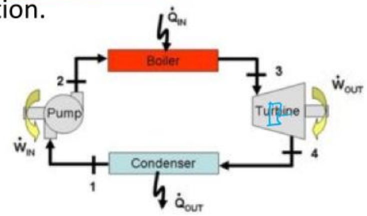
When you do it reverse, it is condensation, vapourization and condensation of a working fluid. Of any fluid, that is what I discussed in the beginning, but we are comfortable with water, so we take water. Which allows the efficient energy transfer and high thermal efficiency is nothing but vapor power cycle. As I told you there will be a pump where water is pumped into the system then the water is taken to the boiler where there is a phase change. You can have single phase two phase generally we will have single phase.

So, the steam is passed through the steam hits the turbine. So, the turbine has pressure here it is pressure and temperature both are very high. So, when it comes out it tries to do work, and then the left pressure is low, temperature can be low or it can be the same. Generally, it is low. Then we try to pass this into the steam, whatever is there pass through a condenser. In the condenser it gets converted. Again a phase change happens from steam to liquid it happens, and then we try to send it back to the pump. It is a closed loop system. You can have an open loop system, you can reject this out or you can use it in a closed loop system.

Today we use it as closed loop system and every time when the loop is running we might lose the water in terms of vapor which gets out maybe 3%, 4%. So it is not a big loss but still it is a closed loop. Their primary objective is to convert thermal energy derived from the fuel combustion or other heat sources into mechanical work. Which can then be transformed into electrical energy. This is what I said, turbine blade, the work whatever is done gets attached to a generator, generator to electricity.

Vapour Power Cycles

- The idealized Rankine cycle, often used to model steam power systems, serves as a benchmark for understanding more complex real-world applications.
- Vapour power cycles are central to sustainable and large-scale power production and studying their thermodynamic behavior enables engineers to optimize performance, reduce fuel consumption and comply with environmental regulations.
- By analyzing energy and entropy changes at various stages of the cycle, we gain insights into both the limitations imposed by the second law of thermodynamics and the engineering trade-offs necessary for practical implementation.



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The idealized Rankine cycle often used to model steam power system serves as a benchmark for understanding more complex real-world application. So, we saw the same system here. It is the same schematic diagram used here. The vapor power cycle are central to sustainable and large scale power production. And studying their thermodynamic behavior enables engineer to optimize the performance.

At what speed should I run the pump? At what energy or temperature should I try to run the boiler? The boiler in the schematic looks very simple, but in reality, it is a very tough machine to handle. Then, turbine blades: the blade geometry is a very difficult task, and you will not have just one blade attached to the shaft; it will be a series of blades. By analyzing energy and entropy changes at various stages of the cycle, so why? Because you have heat that comes out, and then you have entropy changes.

These two are very important. By analyzing the energy and entropy changes at various stages of the cycle, we gain insight into both the limitations imposed by the second law of thermodynamics. Friends, throughout the course, you should remember the zeroth law, first law, and second law. And the engineering trade-offs necessary for practical implementation.

Carnot vapour Power Cycle

- The Carnot vapour cycle is an idealized thermodynamic cycle that represents the **maximum possible efficiency** any heat engine can achieve operating between two temperature limits.
- Unlike the Carnot gas cycle, which uses ideal gases, the vapour cycle involves **phase change (vapourization and condensation)** of a working fluid like steam.
- Though it is impractical due to difficulties in compressing wet vapour and handling two-phase flow in turbines and pumps, it is useful as a **benchmark** for real vapour cycles such as the Rankine cycle.

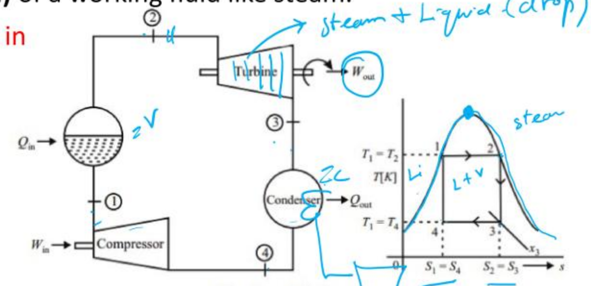

Fig. *Carnot Cycle*

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The Carnot Vapour Cycle is an idealized thermodynamic cycle. Why do we always go for the Carnot Cycle? Because here, to a large extent, we remove all the assumptions. Or I would put it this way: we try to have a lot of assumptions, and then we try to simplify the system to get the output. So, the Carnot Vapour Cycle is an idealized thermodynamic cycle that represents the maximum possible efficiency any heat engine can achieve operating between two temperature limits. So, unlike the Carnot gas cycle, which uses an ideal gas, the vapour cycle uses a phase change: vaporization and condensation. Vaporization—here it is vapour, here it is condensed—of a working fluid like steam.

Though it is impractical due to difficulties in compressing wet vapour and handling two-phase flow in turbines and pumps, it is useful as a benchmark for real vapour cycle such as Rankine cycle. When we plot the TS diagram, that is what I said, here operating between two temperature limits, you have a TS diagram, you can see here the temperature. First, this is a normal curve, you know what is it. So, here it is steam, here it is liquid and inside this is liquid plus vapor, vapor is the steam, right. So, here is a critical point.

So, this is the diagram where in which TS diagram which shows at what stage the working fluid is in which state, right? So, now, this is the basic curve and then in this curve you can see 1 to 2 where there is 1 to 2 1 to 2 right where the temperature is constant 1 to 2 where the temperature is constant right. And then 2 to 3, there is an entropy drop. 2 to 3, there is an entropy drop where turbine blade is rotated. From 3 to 4, from 3 to 4, there is a condensation happening.

Again, in an ideal cycle, we assume that the temperature is uniform. Then, 4 to 1, we try to increase the temperature. 4 to 1, we try to increase the temperature. So, you see here. So, a 1 to 4, 1 to 4 and then 2 to 3, 2 to 3, there is a same entropy. So, S1 equal to S4, S2 equal to S3.

So, this is a typical idealistic TS diagram for the Carnot Vapour Cycle. So, I would like to reiterate this point; though it is impractical due to difficulties in compressing wet vapour and handling two-phase flow in a turbine. Two-phase flow is very tough to handle. What are the two phases? You will have steam and then you will have a liquid. The liquid, if it exists in droplet form and is coming out with very high pressure, when it hits the turbine blade, it might erode the turbine blade.

And it will also try to cause imbalance. The moment there is erosion, there is an imbalance. The moment there is an imbalance, the efficiency of the output is gone. So, we will always try to have a single phase. Handling two-phase flow in turbines and pumps is the same with respect to pumps also. The compressor, when we do from here, if it has steam plus liquid, the pump will also try to have its difficulty. So, it is useful as a benchmark for real vapour cycles such as the Rankine cycle. So, we do not know the output of a Rankine cycle. So, we try to have a benchmark, then compare the Rankine cycle with it.

Carnot vapour Power Cycle

➢**Process 1–2: Isothermal Heat Addition (Evapouration)**

Occurs at constant high temperature T_2. Working fluid absorbs heat Q_{in} and vapourizes at saturated conditions.

➢**Process 2–3: Isentropic Expansion**

High-pressure saturated or superheated vapour expands in a turbine. Produces work while temperature drops from T_2 to T_3.

➢**Process 3–4: Isothermal Heat Rejection (Condensation)**

At constant low temperature T_3. Heat Q_{out} is rejected as the vapour condenses into saturated liquid.

➢**Process 4–1: Isentropic Compression**

Liquid is compressed back to high pressure using a pump. No heat exchange; entropy remains constant.

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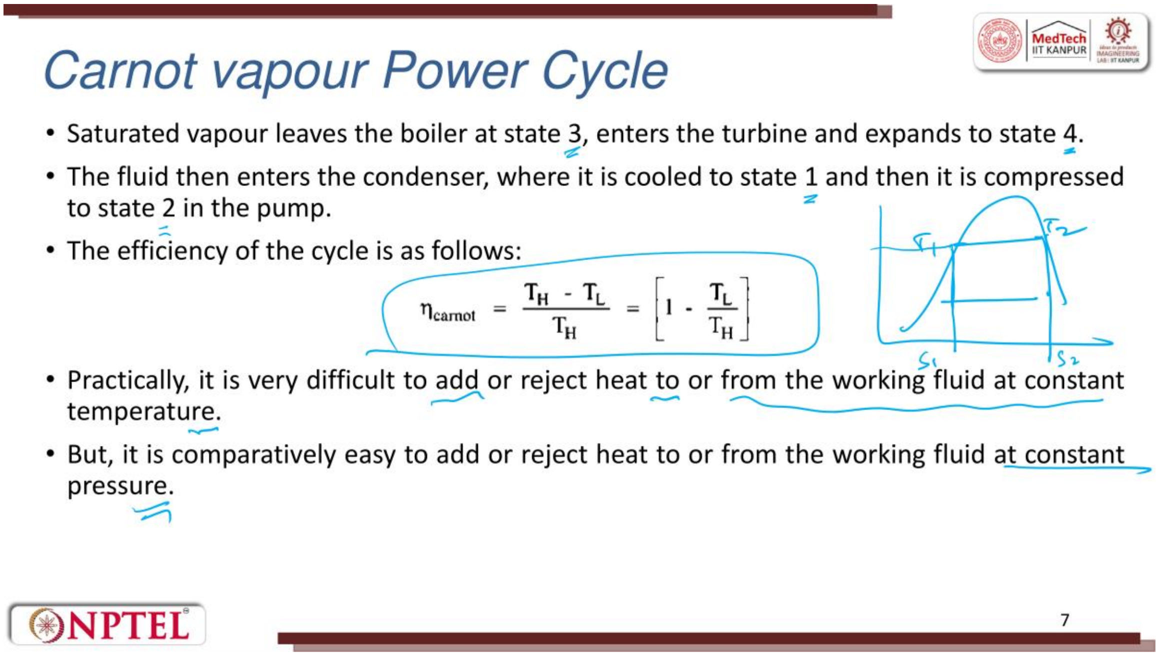
So, 1 to 2 follows isothermal heat addition, which is the evaporation process 1 to 2. So, it occurs at a constant high temperature T2, where the working fluid absorbs heat Q in and vaporizes at a saturated condition. So, friends, from now onwards, please start noting out the saturated condition. What is a saturated condition? So, 2 to 3 is isentropic expansion. The high-pressure saturated or superheated vapour expands into a turbine.

So, where it tries to heat at a turbine where pressures are high and temperatures are high. So, high pressure saturated or superheated vapor expands in the turbine produces work while temperature drops from T2 to T3. T2 to T3 then isothermal heat rejection which is condensation here at constant low temperature T3 heat is rejected as the vapor condenses into saturated liquid. So, now what we do is in reality here also when the heat comes out right with the condenser when we say the heat comes out again here there will be lot of heat residual heat. So, here we once again tap it from here and attach one more cycle and we declare this one as a high cycle and this one as a low cycle.

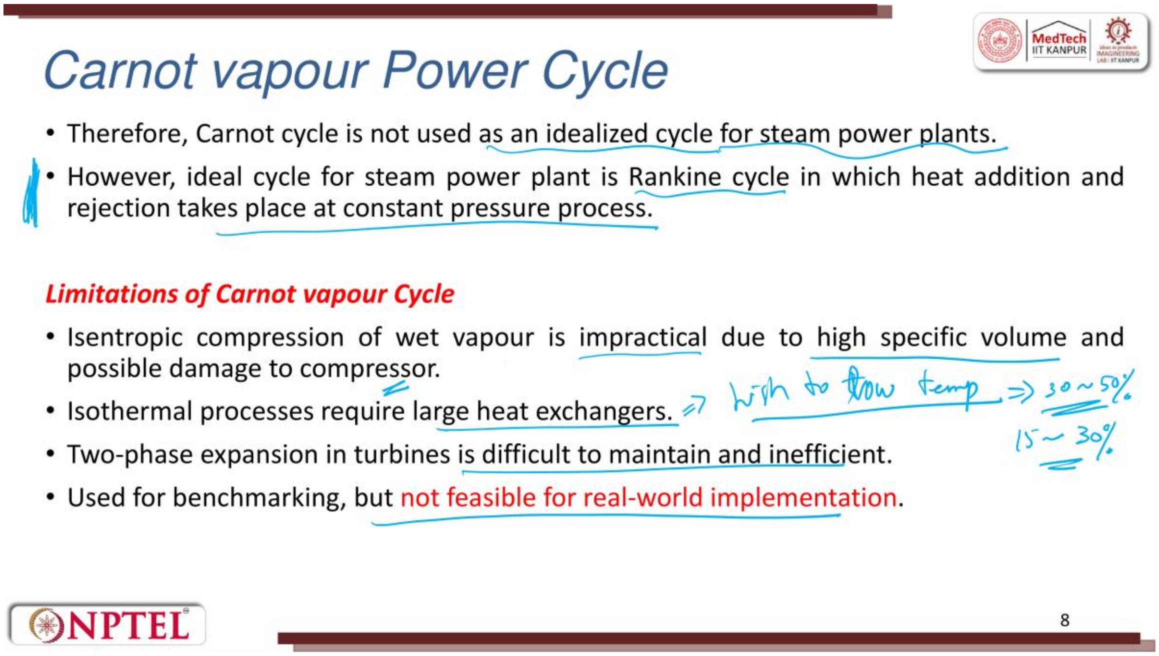
So, that the heat whatever gets rejected still it is used. So 4 to 1 is isentropic compression. Liquid is compressed back to high pressure by using a pump. No heat exchange happens. The entropy at this point is constant. If you go back to the diagram, you can see the same representation.



So the saturated vapor leaves the boiler at stage 3 or state 3, enters the turbine and expands to state 4. The fluid then enters the condenser where it is cooled to state 1 and then it is compressed to state 2 in the pump. The efficiency of the entire cycle is found out by

$$\eta_{carnot} = \frac{T_H - T_L}{T_H} = \left[1 - \frac{T_L}{T_H}\right]$$

Practically, it is very difficult to add or reject heat to or from the working fluid at a constant temperature. Where is the constant temperature coming from? T-S diagram, T1, T2. This is S1 and S2. But it is comparatively easy to add or reject heat to and from the working fluid at constant pressure. Temperature is difficult; pressure is easy.



Therefore, the Carnot cycle is not used as an idealized cycle for steam power plants. However, the ideal cycle for steam power plants is the Rankine cycle, in which heat addition and rejection take place at a constant pressure process. So, this point is very important. Why are we not using the Carnot cycle as an idealized cycle in steam power plants? So, the limitation of the Carnot Vapour Cycle is that isentropic compression of wet vapour is impractical.

Because it has a very high specific volume, possibly it can damage the compressor. So, isentropic compression of wet vapour is impractical. The isothermal process requires a large heat exchanger. A heat exchanger is where heat transfer happens between high and low temperatures. So, when it is done from high to low temperature, there is a heat exchanger involved, and the majority of heat exchangers work with 30 to 50 percent efficiency.

I am talking about very very generic, but majority of the time it operates between 50 into 30 percent efficiency. So, you see there is a huge heat loss or energy loss. Two phase expansion in turbine is difficult to maintain and it is inefficient. Under the used for benchmarking but not feasible for real world implementation is the limitation of Carnot vapor cycle. So, this pushes us to study about the Rankine cycle.

Rankine Cycle

- The Rankine cycle is the fundamental thermodynamic cycle that underpins the operation of steam-based thermal power plants, which produce a significant portion of the world's electricity. It overcomes the Carnot cycle's impracticality of compressing a wet vapour by instead compressing the working fluid in its liquid state.
- The cycle involves four main processes – **pumping, heating, expansion and condensation** – each of which is thermodynamically more feasible and mechanically more efficient than the corresponding Carnot cycle processes.
- The Rankine cycle is widely used due to its flexibility and adaptability to various modifications aimed at improving efficiency and output, such as superheating, reheating, and regenerative feedwater heating.

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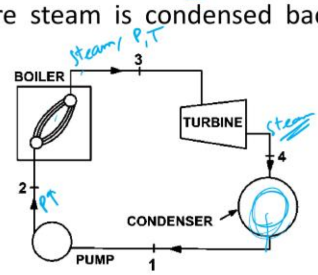
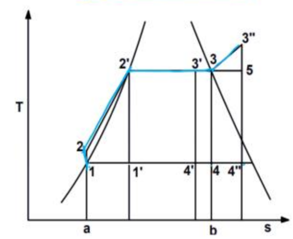
Rankine cycle is the fundamental thermodynamic cycle that underpins the operation of steam-based thermal power plant, which produces a significant portion of the world's electricity. It overcomes Carnot cycle's impracticability of compressing a wet vapor by instead compressing the working fluid in its liquid state. So, this is where is the change impractical of compressing a wet vapour. by instead compressing the working fluid in the liquid state. This cycle involves pump, heating, expansion and condensation. Pump, heating. So, each of which is thermodynamically more feasible and mechanically more efficient than corresponding to the Carnot cycle process.

The Rankine cycle is widely used due to its flexibility and adaptability to various modifications which are aimed to improve the efficiency of the output such as superheating, reheating, regenerative feed water heating, all these things are possible in a Rankine cycle. So, you can keep on be adding some subsystems to the main system and try to extract heat so that you can you are more efficient.

Rankine Cycle

- The cycle begins with pumping of saturated liquid water to a high pressure followed by heating in a boiler where it is converted into dry saturated or superheated steam.
- This high-energy steam then expands through a turbine to produce mechanical work, which is typically converted into electricity using a generator.
- After expansion, the low-pressure steam is condensed back into saturated liquid in a condenser, completing the cycle.





Block diagram Rankine power cycle   T-s diagram Rankine power cycle

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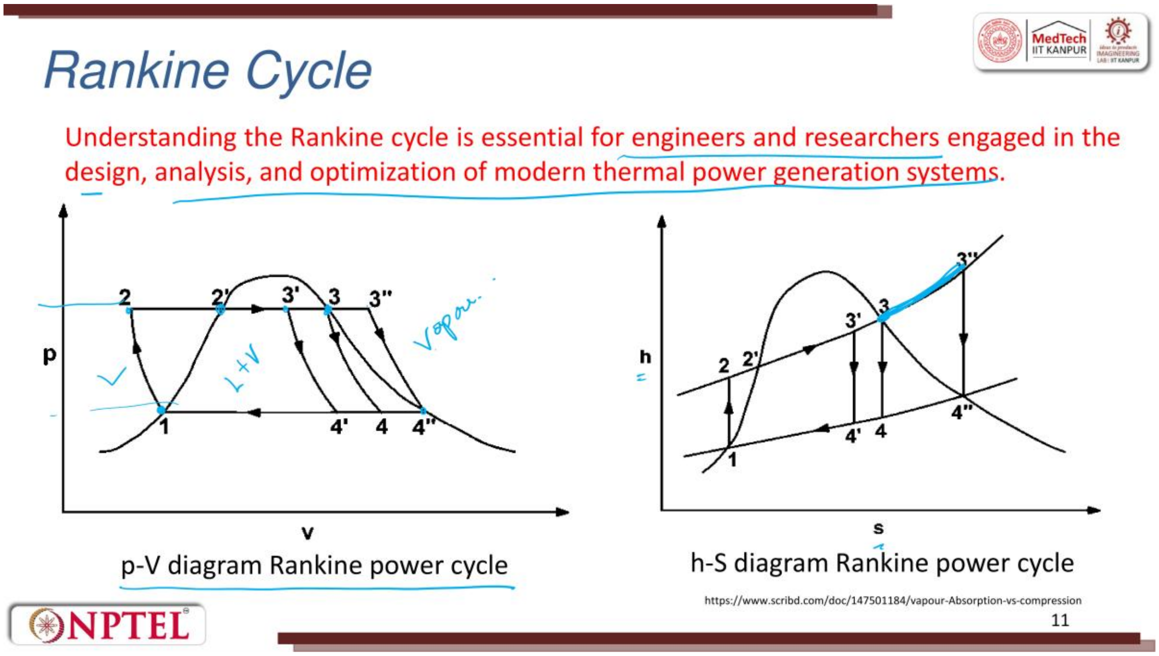
So, the cycle begins with pumping a saturated liquid water at a high pressure. So, pumping. So, you say here; water comes here, pump happens here at a high pressure. Pressure increases. High pressure followed by heating in a boiler where it gets converted into a dry, saturated or a superheated steam.

So, what comes out here is steam with very high pressure and temperature. The high-energy steam then expands through the turbine and produces mechanical work, which is typically converted to electricity using a generator. This is what I said. After expansion, which happens in the turbine, what is expansion? The pressure goes down.

After expansion, the low-pressure steam, whatever comes out here, will also be steam. It is not that you will not have steam. You will have steam. The low-pressure steam is condensed here back into a saturated liquid in a condenser, completing the cycle. So, if we draw a TS diagram, it follows 1 to 2, 2 to 2 dash, 2 dash to 3, 3 to 3 double dash. From 3 double dash, it falls down to 4 double dash, and from 4 double dash, it gets connected to 1. So, you can see or the system can be drawn like this: 1, 2, 3, and 4.

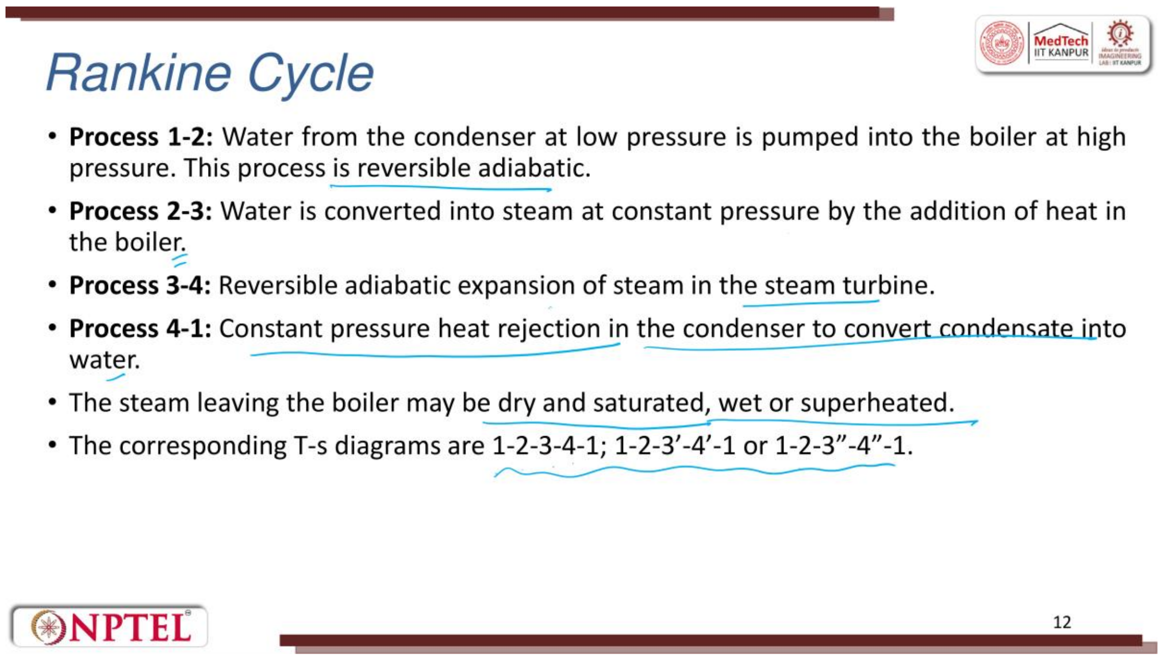


So, understanding the Rankine cycle is essential for engineers and researchers engaged in the design, analysis, and optimization of modern power generation systems. So, you have a P-V diagram. 1 is the stage where you have pumping; from 1 to 2, pressure increases, the volume is compressed, and volume goes down. From there, you move to 3, where there is expansion of volume, but the pressure is constant.

From 3, you come down to 4, where you reduce the pressure and further expand the volume. Then, when you want to complete the cycle from 4, we try to compress at the same pressure. This is a normal cycle. The other way round is, you can try to go from here to 2 dash, where the volume is compressed and the pressure is increased. Pressure, let us assume P1, this is P2, the pressure is increased.

Then from there, you allow the volume to expand. You know the volume to expand and then what you have is after the volume gets expanded there is a increase in the further volume increase to 4 dash. Then from 4 dash you go to 1. This is one path. The other way around is you move from 1 to 4. 2 or to 2 dash from there you move to 3 double dash.

So, why we do we move to 3 double dash because this is steam this is liquid plus vapor this is liquid. So, if I want to make it this I will make it as vapor. So you enter into the vapor regime from 2 to 3 dash and from 3 dash you try to reduce the pressure which happens in a turbine and which comes and hits at the downside of the curve where there is a volume expansion also happening. From 4 double dash back to 1. So PV diagram Rankine power cycle goes in this form. When we wanted to put the same thing in a TS diagram or a HS diagram, you will try to have this phenomena.



1 to 2, the water from the condenser at low pressure is pumped into the boiler at high pressure. In this process is reversible adiabatic. So, water at low pressure is pumped to boiler at high pressure and it is reversible adiabatic. Note down this point.

The water is converted into steam at a constant pressure by the addition of heat in the boiler. 2 to 3, constant pressure. 3 to 4 is reversible adiabatic. So here it is reversible adiabatic expansion of steam in the steam turbine. At 4 to 1, there is a constant pressure heat rejection in the condenser to convert condensated into water.

The steam leaves the boiler may be dry or unsaturated, wet or superheated. The corresponding T-S diagram can be 1, 2, 3, 4, 1 which we saw. It can be 1, 2, 3 dash, 4 dash, 1 or it can be 1, 2, 3 double dash, 4 double dash, 1. It can try to work on any of these cycles.

Rankine Cycle: Thermal Efficiency

Thermal efficiency η is given by:

$$\eta = \frac{W_{\text{net}}}{Q_{\text{in}}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

Where:

h_1: Enthalpy at condenser outlet

h_2: Enthalpy after pumping

h_3: Enthalpy after boiler (steam entry to turbine)

h_4: Enthalpy after turbine expansion

So, the thermal efficiency overall can be figured out

$$\eta = \frac{W_{\text{net}}}{Q_{\text{in}}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

So, this is how you try to find out the thermal efficiency of the process, the net work. So, all the losses happening everywhere, and then you try to figure out what the output is, divided by Q in. So, h1 is the enthalpy at the condenser output, h2 is the enthalpy after pumping, h3 is the enthalpy after boiling, and h4 is after the turbine expansion.

Rankine Cycle: Ideal for Steam power plant

***Reasons for Considering Rankine Cycle as an Ideal Cycle For Steam Power Plants*:**

1) It is very difficult to build a pump that will handle a mixture of liquid and vapour at state 1 (refer T-s diagram) and deliver saturated liquid at state 2'.
2) It is much easier to completely condense the vapour and handle only liquid in the pump.
3) In the rankine cycle, the vapour may be superheated at constant pressure from 3 to 3" without difficulty.
4) In a Carnot cycle using superheated steam, the superheating will have to be done at constant temperature along path 3-5.
   During this process, the pressure has to be dropped.
   This means that heat is transferred to the vapor as it undergoes expansion doing work. This is difficult to achieve in practice.

So, the reason for considering the Rankine Cycle as an ideal cycle for a steam power plant is that it is very difficult to build a pump that will handle a mixture of liquid and vapor at state 1 and deliver saturated liquid at state 2.

But that's why we try to use the Rankine Cycle. It is much easier to completely condense the vapor and handle only liquid in the pump. That is easy. You bring it to one state; water can be pumped. In the Rankine cycle, the vapor may be superheated at constant pressure.

That is from 3 to 3 double dash without any difficulty. So, what I am trying to say is that it can move from 3 to 3 double dash easily without any problem. In the Carnot cycle, using superheated steam, the superheating will have to be done at constant temperature along path 3 to 5. During this process, the pressure has to drop. So, when we are trying to increase the temperature, the superheating will have to be done at a constant temperature along path 3 to 5.

So, during this process, the pressure has to drop. This means that the heat is transferred to the vapor as it undergoes expansion during work. This is practically impossible or very difficult. That is why we always try to talk about the Rankine cycle when the vapor cycle is discussed.

Modified Rankine Cycle

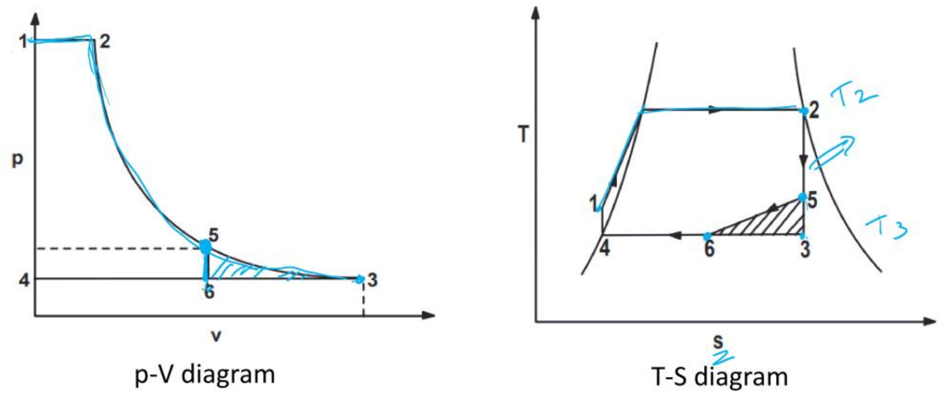
- The basic Rankine cycle, while widely used, suffers from certain limitations—primarily its moderate efficiency and moisture content at the turbine exit.
- To address these shortcomings, **modified Rankine cycles** are employed.
- The two most common modifications are:

1. **Reheat Rankine Cycle**: Improves turbine work and reduces moisture content.
2. **Regenerative Rankine Cycle**: Increases thermal efficiency by preheating feed water.

- These modifications make power plants more efficient, reduce fuel consumption and extend equipment life.

Modified Rankine Cycle

Cycle 1-2-5-6-4 is called as the "modified Rankine cycle".



https://www.scribd.com/doc/147501184/Vapor-Absorption-vs-compression

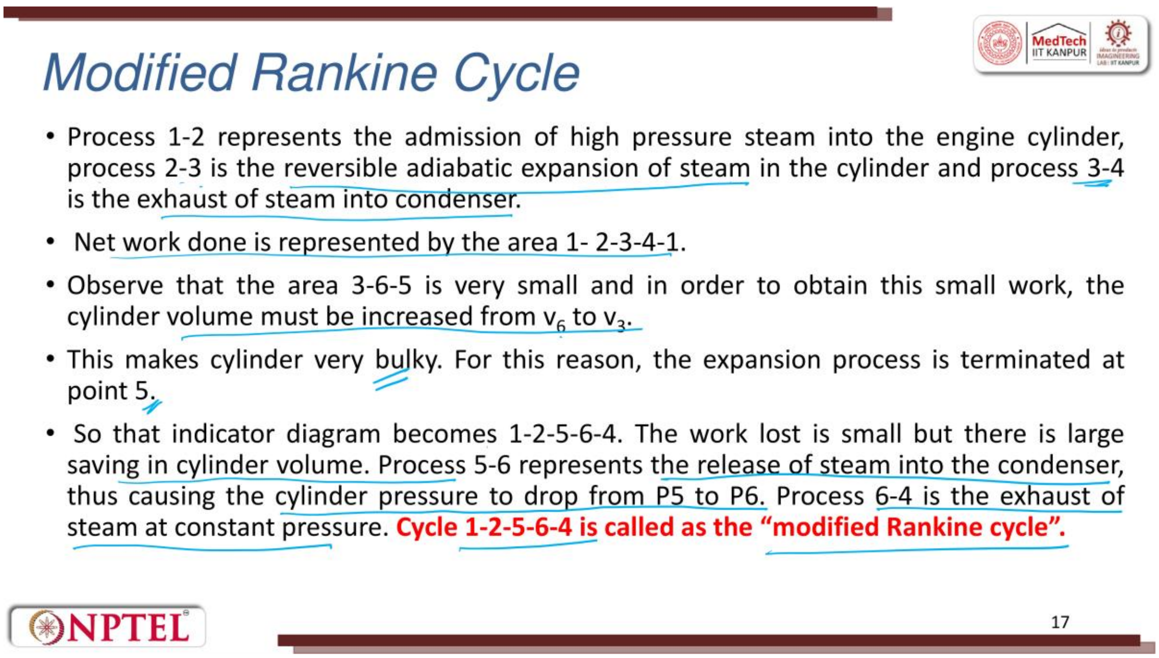
The basic Rankine cycle, while widely used, suffers from some limitations. Primarily, its moderate efficiency and the moisture content at the turbine exit impose some limitations. So, we are trying to convert this Rankine cycle into a modified Rankine cycle. To address this shortcoming, we are moving into a modified Rankine cycle. There are two most common modifications made. One is the reheat Rankine cycle, and the other is the regenerative Rankine cycle.

The reheat Rankine cycle improves turbine work and reduces moisture content. Whereas the regenerative Rankine cycle increases thermal efficiency by preheating the feedwater. So, what we are trying to say is, wherever heat is being rejected, do not simply release it into the atmosphere. Take that heat, try to convert the liquid into steam, and then use it in the process. So, improving the turbine work and reducing the moisture content is achieved by reheating.

So when you reheat, the moisture content will be reduced. So it gets into superheated. Regenerative is the thermal efficiency can improve. These modifications make power plant more efficient, reduce the fuel consumption and extend the life of it. So the modified Rankine cycle, the cycle goes from 1 to 2 where constant pressure, then 2 to 3 there is an expansion in the volume and there is a reduction in the pressure.

While going to 3, in between we try to have an intermediate point which is called as 5. From 5, we try to drop down to 6, the pressure is further dropped down and then we close the cycle to 4. So, this is the PV diagram 1, 2, 5, 6 and 4 is the PV diagram for modified Rankine cycle. The explanation we have given it early. If we want to put the corresponding TS diagram, it is going to be 1.

So, we are going to go to a temperature T1 T2 and then maintain the S up to stage 2, where the entropy is increased, S is increased. And then, from 2 we drop it down to 3. The temperature is reduced from T2 to T3 and the entropy is constantly maintained. So rather than going to 3, we stop at 5 corresponding here. Then we join it with 6, 5, 6, 4. So this dashed area, we will see what is the use of it.



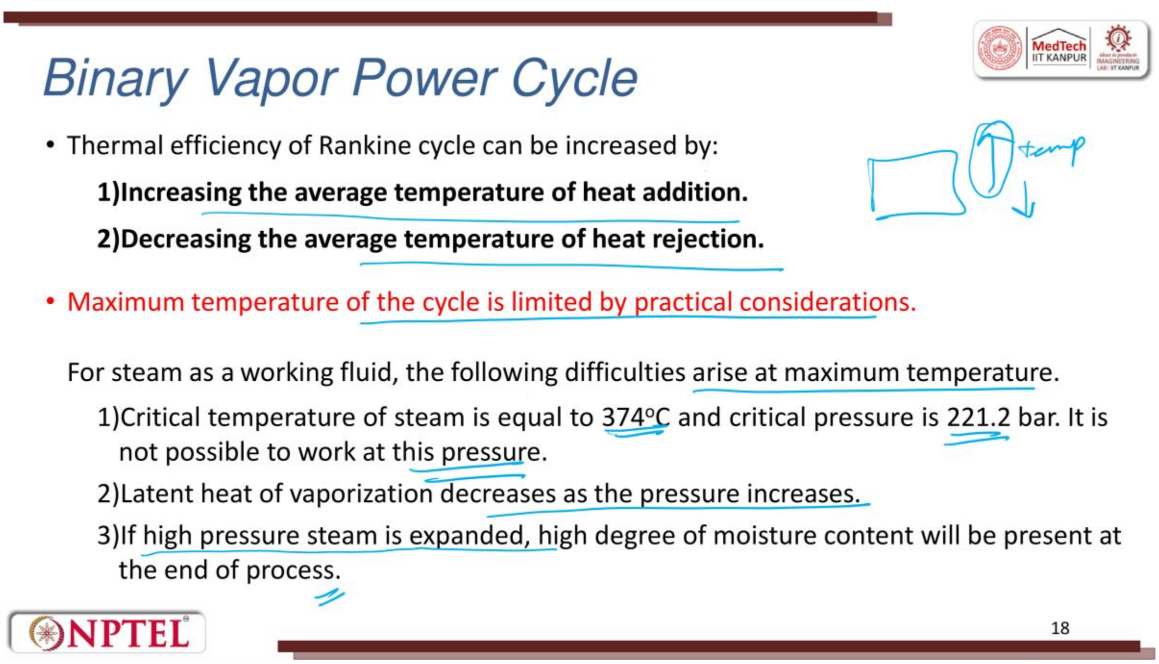
So, the process 1 to 2 represents the admission of high-pressure steam into the engine cylinder. The process 2 to 3 is the reversible adiabatic expansion of steam in the cylinder. And process 3 to 4 is the exhaust of the steam into the condenser. So, the net work done in the area 1 is nothing but 1, 2, 3, and 4. 1. This is the net work area done.

Observe the area 3, 5, 6. 3, 5, and 6. This area. So, it is also 3, 5, 6. It is very small. And, in order to obtain this small work, the cylinder volume must be increased from V6 to V3. The volume has to be extended, OK. This makes the cylinder very bulky. For this reason, the expansion process is terminated at point number 5. So, in order to have a smaller volume and a smaller machine, we stop at 5. So, the indicator diagram becomes 1, 2, 5, 6, 4 instead of 1, 2, 3, 4, 1. 1, 2, 5, 6, 4.

The work lost is small, but there is a large saving in cylinder volume. If you want to go from 6 to 3, the cylinder volume goes very high. So, we also have to optimize the volume of the machine. So, we stop at 5 and drop it to 6. So, the indicator diagram becomes 1, 2, 5, 6, 4.

The work lost is small, but there is a large saving in the cylinder volume. If you reduce the cylinder volume, so then the efficiency of the engine goes high. The process 5 to 6 represents the release of steam into the condenser. 5 to 6, the process 5 to 6, there is a release of energy into the condenser. thus causing a cylinder pressure to drop from P5 to P6, from P5 to P6, cylinder volume increase P5 to P6, right.

The process 6 to 4 is then exhaust of steam at constant pressure. So, 1 to 5, 6, 4 is called as a modified Rankine cycle. 1, 2, 3, 4 is the Rankine cycle, 1, 2, 5, 6, 4 is the modified Rankine cycle.

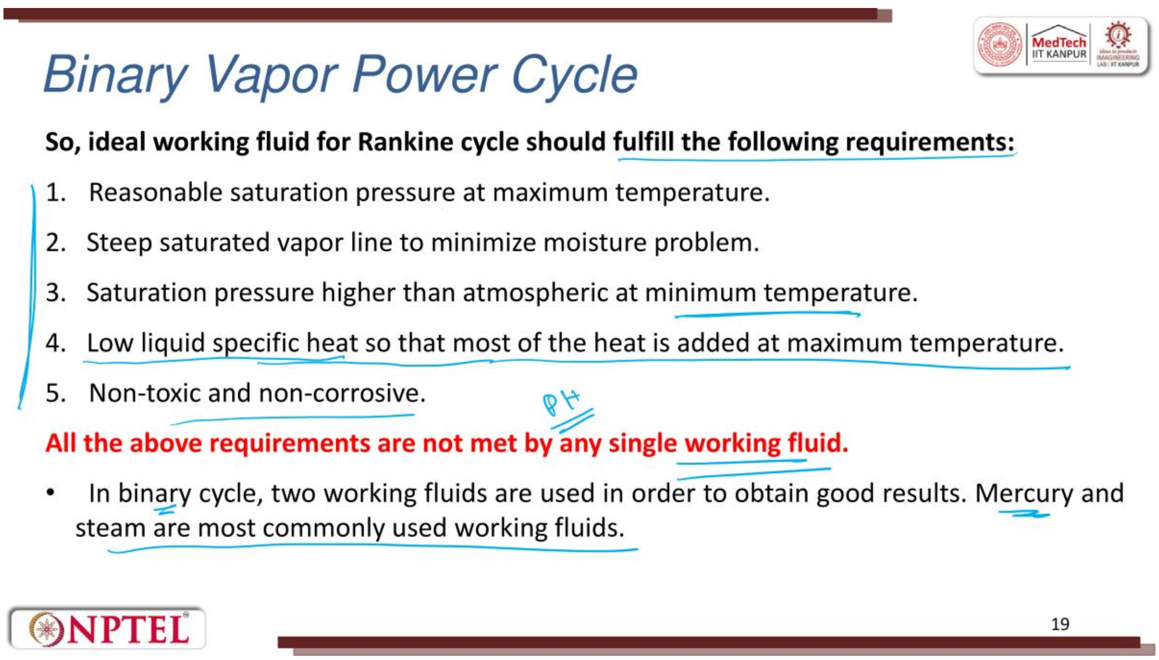


So, the thermal efficiency of the Rankine cycle can be increased by increasing the average temperature of the heat addition and by decreasing the temperature in the heat addition. So, basically you have a liquid you heat it.

So, you try to increase the temperature more steam. So, more steam more work and when it is also getting converted into water you try to. So, decrease in the average temperature of heat rejection. So, the thermal efficiency of the Rankine cycle can be done only by these two. So, the maximum temperature of a Rankine cycle is limited by practical consideration.

So, temperature how much maximum you can go. So, that depends on the material what you use in the machine. So, you cannot keep on be going to infinite you have to stop at somewhere so that the material does not get softened while doing the process. So, maximum temperature of the cycle is limited by the practical consideration for steam as a working fluid the following difficulty arises at maximum temperature. The critical temperature of steam is equal to 374 degree Celsius and the critical pressure is 2 to 1 bar.

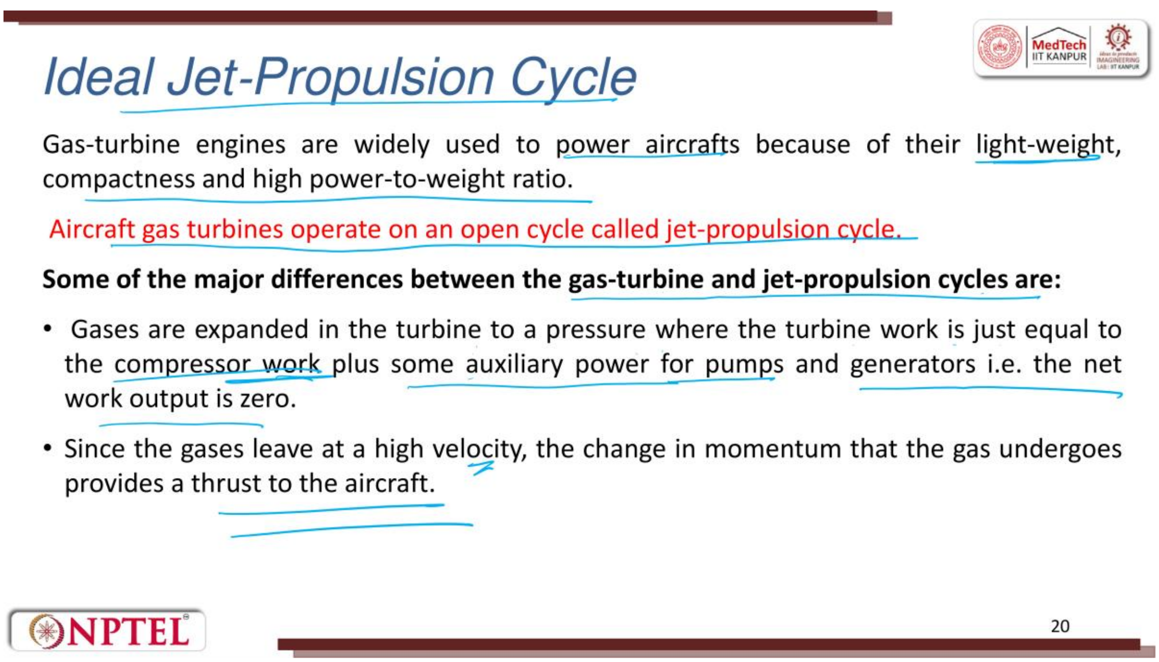
It is not possible to work at that pressure. It is very difficult to work at that pressure, the temperature. Latin heat of vaporization decreases as the pressure increases. If high pressure steam is expanded, the high degree of moisture content will present at the end of the process.



So, ideal working fluid for Rankine cycle should fulfill the following requirements. All the things are very important. Reasonable saturation pressure at maximum temperature. Then steep saturated vapor line to minimize moisture problem. Saturation pressure higher than the atmospheric pressure at minimum temperature. And then low liquid specific heat so that most of the heat is added at maximum temperature.

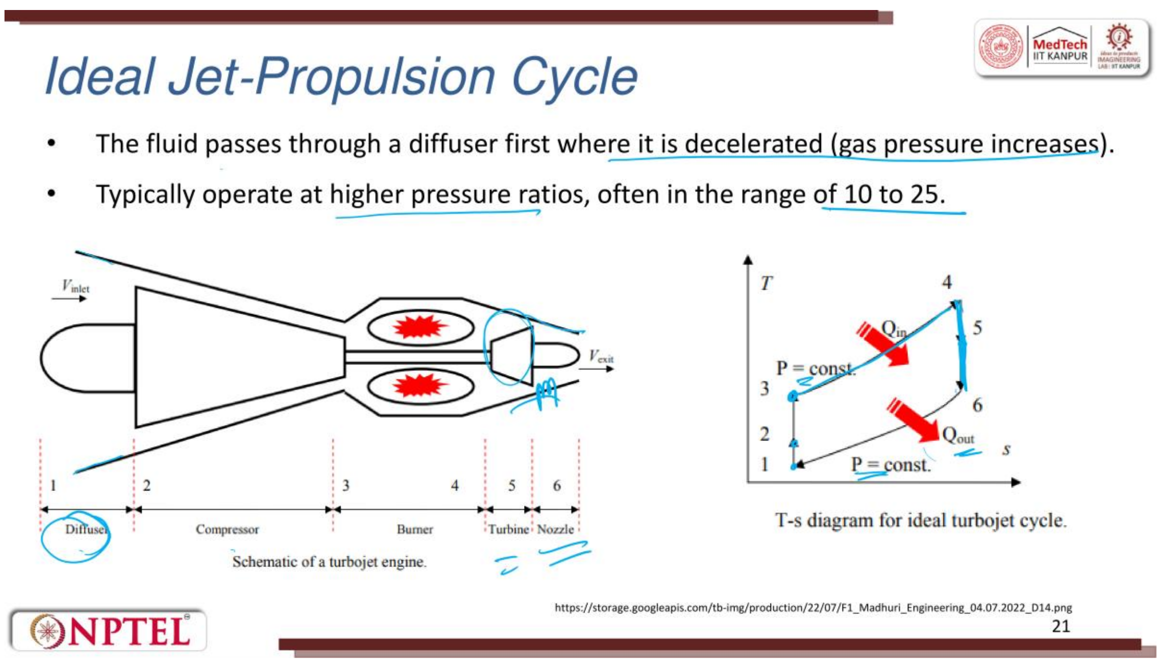
Non-toxic and non-corrosive working fluids you have to consider. You can get by changing the pH of water. Adding some thing towards acidic moving towards basic. You can do all those things. But it will try to bring in non toxic and non corrosive. It should not corrode the thing. So, reasonable saturation pressure at maximum temperature we saw for 221 bar. For water steep saturation vapour line to minimize the moisture problem, then saturation pressure higher than the atmospheric pressure low liquids specific heat. So please check what is low liquid specific heat. So, for maximum temperature all the above requirements are not met by a single working fluid.

So, in binary cycle we try to have two different working fluids that is why it is called as binary cycle. In binary cycle we will have two working fluids and used in order to obtain good results. So, mercury and steam are most commonly used working fluids. So, next we will move to ideal jet propulsion cycle. So, this is propulsion cycle is always used in the aircrafts.



So, the gas-turbine engine are widely used to power aircrafts because of their light weight compact and high power to weight ratio. See the same vapor pressure you cannot put it inside an aeroplane and take it and go. In airplane also you need to have very high speeds coming up. So we always have aircraft gas-turbine operate on a open cycle called jet propulsion cycle. Some of the major difference between gas-turbine and jet propulsion cycle are the gas are expanded in the turbine to a pressure where the turbine work is just equal to the compressor work.

Plus some auxiliary power for pumps and generators. The net work output is zero. The major difference between the gas-turbine and jet propulsion cycle is that the gas expands in the turbine to a pressure where the turbine work is just equal to the compressor work, plus some auxiliary power for pumps and other generators. Since the gas leaves at a very high velocity, the change of momentum that the gas undergoes provides thrust to the aircraft. Now, you should understand, friends, how you get the thrust while moving in a plane. The gas has to leave at very high velocities; then only you get that thrust, then only you can go at that high speed.

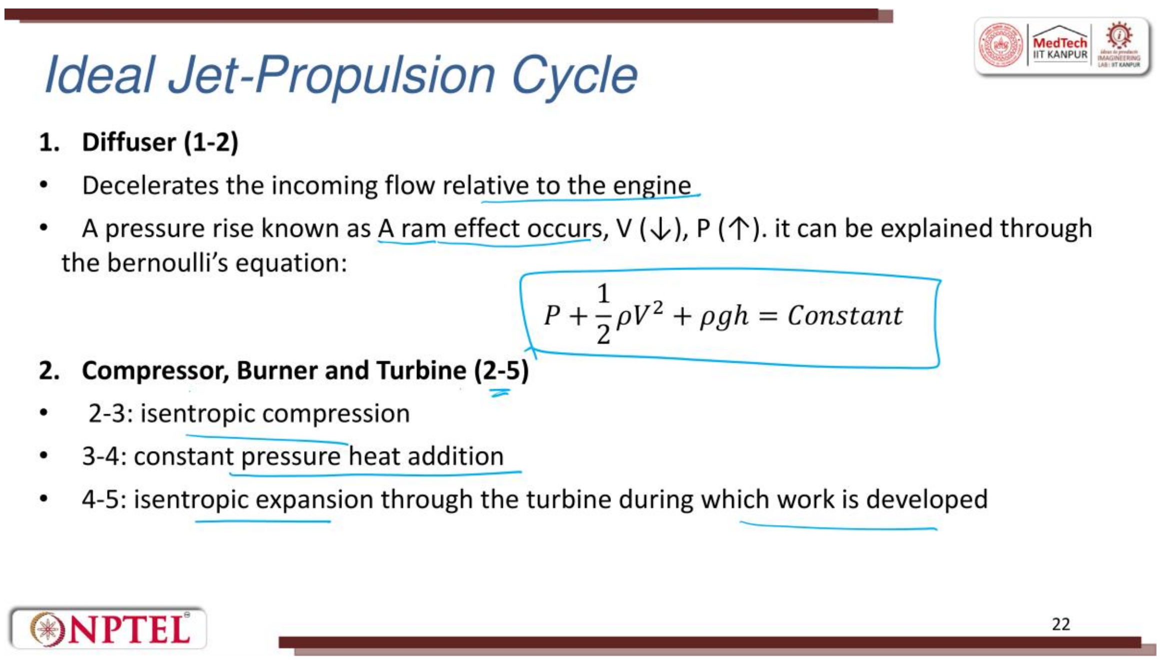


So, in an ideal jet propulsion cycle, the fluid passes through a diffuser. So you can see here: first is the diffuser, then you will have a compressor. So, diffuser, compressor—compressor means compressed air. Then you have the compressed air being burned.

So this is what it is. And then you have a turbine which rotates, and then you will have a nozzle through which it exits into the atmosphere. So the fluid passes through a diffuser. What is a diffuser? A diffuser is a portion where it is trying to focus and push forward.

So it is a diffuser. So from the diffuser, it goes into a compressor. So the compressor compresses the air or mixture, whatever it is. Then it tries to get into the burner, turbine blade, and a nozzle. So the fluid passes through the diffuser first, where it is decelerated. The gas pressure increases as it is decelerated.

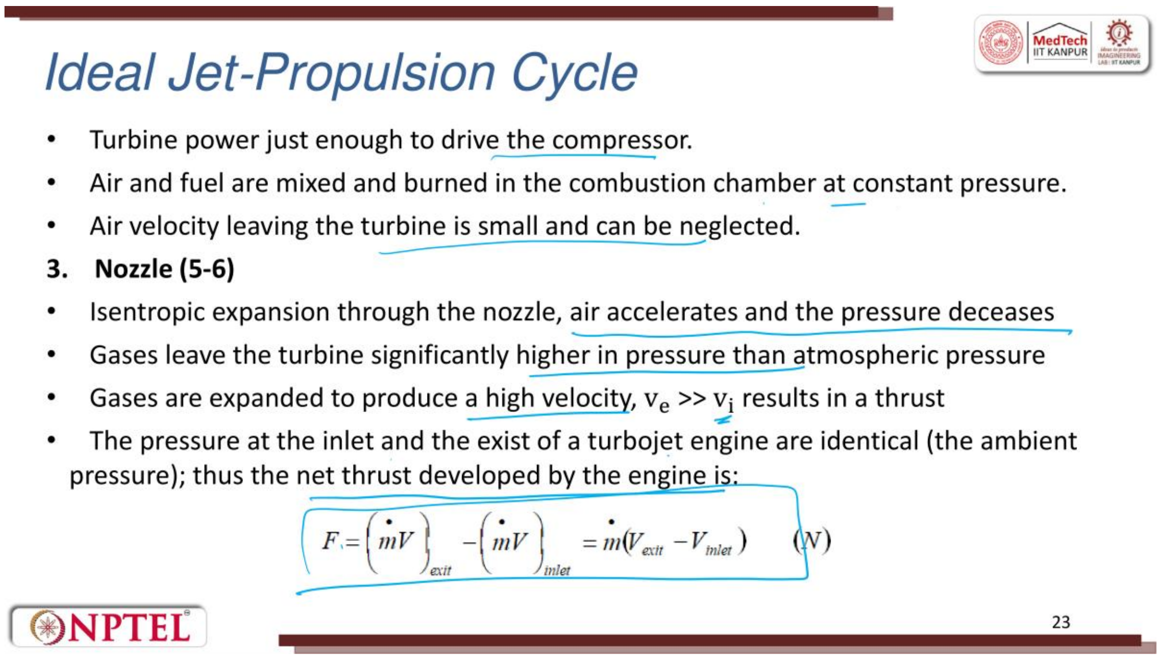
So it is reducing. Typically, it operates at high pressure ratios of 10 to 25. It happens, so the pressure increases. So, if I draw a TS diagram, you can see from 1 to 2, 1 to 3, the pressure increases. Then onwards, the pressure is constant, and the heat is in. Then from 4, 5, 6, there is a reduction in temperature, and the entropy is constant. From 6 to 1, there is constant pressure, but during the same time, the heat Q is rejected. So from 3 to 4 and 6 to 1, these are constant pressure lines.



So a diffuser from 1 to 2 decelerates the incoming flow relative to the engine. First, it decelerates and reduces the flow. A pressure rise, known as a ram effect, occurs. A ram effect occurs.

Velocity reduces, pressure increases. It can be explained through Bernoulli's equation, which is this. Pressure plus half times rho V squared plus rho G H equals a constant. So, the pressure rise, known as the ram effect, occurs where velocity reduces and pressure increases. Then, compressor, burner, and turbine, which is nothing but 2 to 5: 2, 3, 4, and 5.

Where 2 to 3 is isentropic compression, 3 to 4 is constant-pressure heat addition, which we saw. 3 to 4 is constant-pressure heat addition. Isentropic expansion through the turbine, during which the work is developed. 4 to 5, during which the work is developed.



The turbine power is just enough to drive the compressor. Air and fuel are mixed and burnt in the combustion chamber at constant pressure. So, you can see here we have represented the constant-pressure line.

The air velocity leaving the turbine is small and can be neglected. The air velocity leaves the turbine. Where is the turbine? The turbine is here, right? So, 5 to 6 is the nozzle. So, 5 to 6, the straight line is the nozzle.

So, isentropic expansion through the nozzle happens; the air accelerates, and the pressure decreases. So, you can see, velocity and acceleration—these two terms are used. The gas leaves the turbine at a significantly higher pressure than the atmospheric pressure. So, that's how it could gush inside. Sometimes, when you see fighter planes flying in the sky, you can see they leave a straight white line behind them.

So, that's because the gas leaves at a significantly higher pressure than the atmospheric pressure. The gas is expanded to produce high velocity, where V_{exit} is greater than $V_{initial}$, resulting in thrust. The pressure at the inlet and the exit of the turbojet engine are identical. Thus, the net thrust developed by the engine is found using this equation:

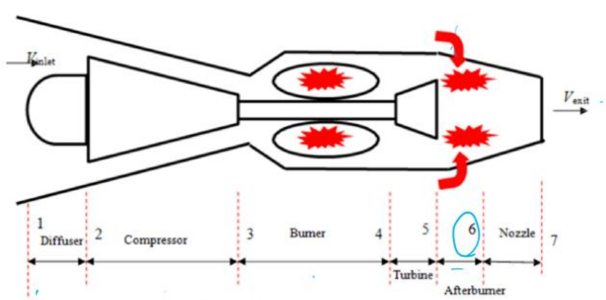
$$F = \left(\dot{m}V\right)_{exit} - \left(\dot{m}V\right)_{inlet} = \dot{m}\left(V_{exit} - V_{inlet}\right)$$

Ideal Jet-Propulsion Cycle

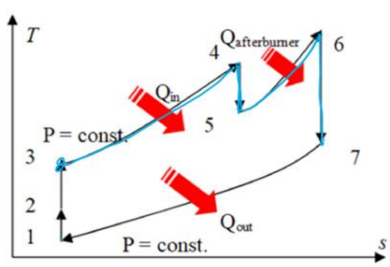
4. Afterburner

- Afterburner is popular in military aircrafts and it is used whenever a need for extra thrust arises, such as for short takeoffs or combat conditions.
- Afterburner is similar to a reheat device; it is located after the turbine and before the nozzle.
- It produces a higher temperature (and pressure) at the nozzle inlet, results in an increase in velocity (and thrust).

Ideal Jet-Propulsion Cycle



Schematic diagram for a turbojet engine with afterburner.



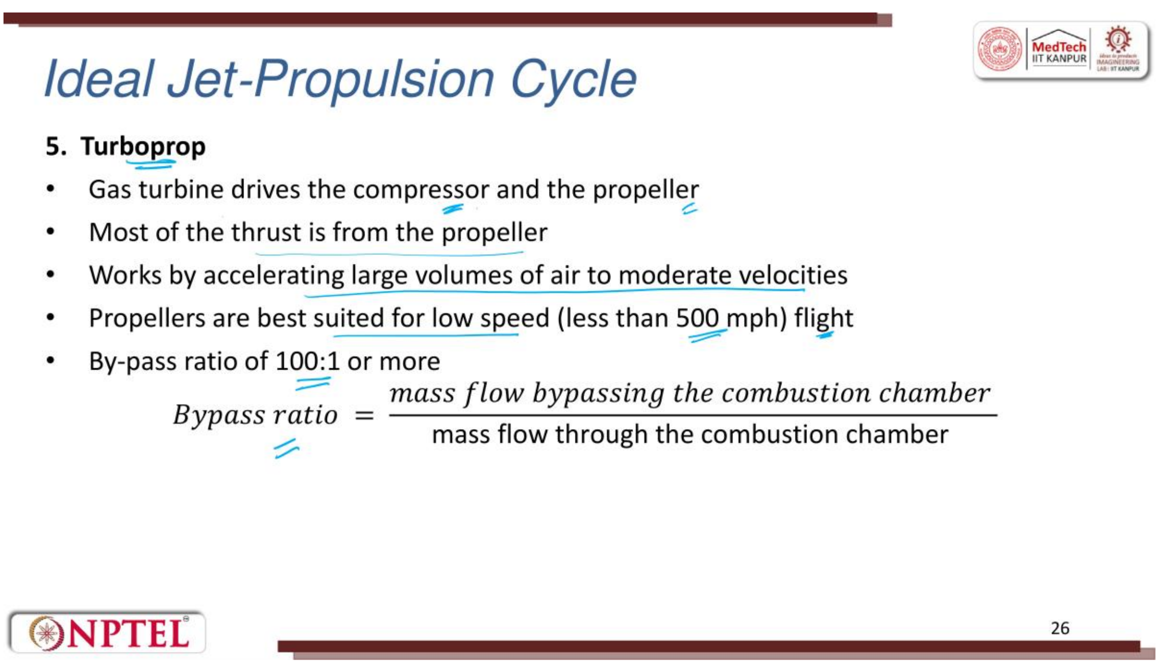
T-s diagram for an ideal turbojet with afterburner cycle.

https://www.researchgate.net/figure/A-schematic-of-a-jet-engine_fig4_323487362

Afterburn—after the burning is done, what comes out? So, afterburn is popular in military aircraft and is used wherever extra thrust is needed, such as for short takeoffs or combat conditions. An afterburner is similar to a reheat device. It is located after the turbine but before the nozzle. After the turbine, before the nozzle—somewhere here.

It produces a higher temperature and pressure at the nozzle inlet, resulting in increased velocity and thrust. So, this is what it is. So, you have a diffuser, a compressor, then you have a burner which happens here, and then you have a turbine which is there. There, an afterburner is put in 656, and then you have it. So now, the same afterburner you do, so you will see there is heat which is also added to the system.

So, you get more thrust. So, 1 to 2 to 3 is compressed. So, the pressure increases, then from 3 to 5 to the turbine, there is heat in which happens, and then at the reheat portion. So, you will have 4 to 5, then again there is heat in which is happening here. Then, from 6 (6 is nothing but the burner) to the nozzle exit, you have a temperature fall down, and then from 7 to 1 is nothing but a constant pressure line where heat is rejected. So, 6 to 7 is a temperature drop.

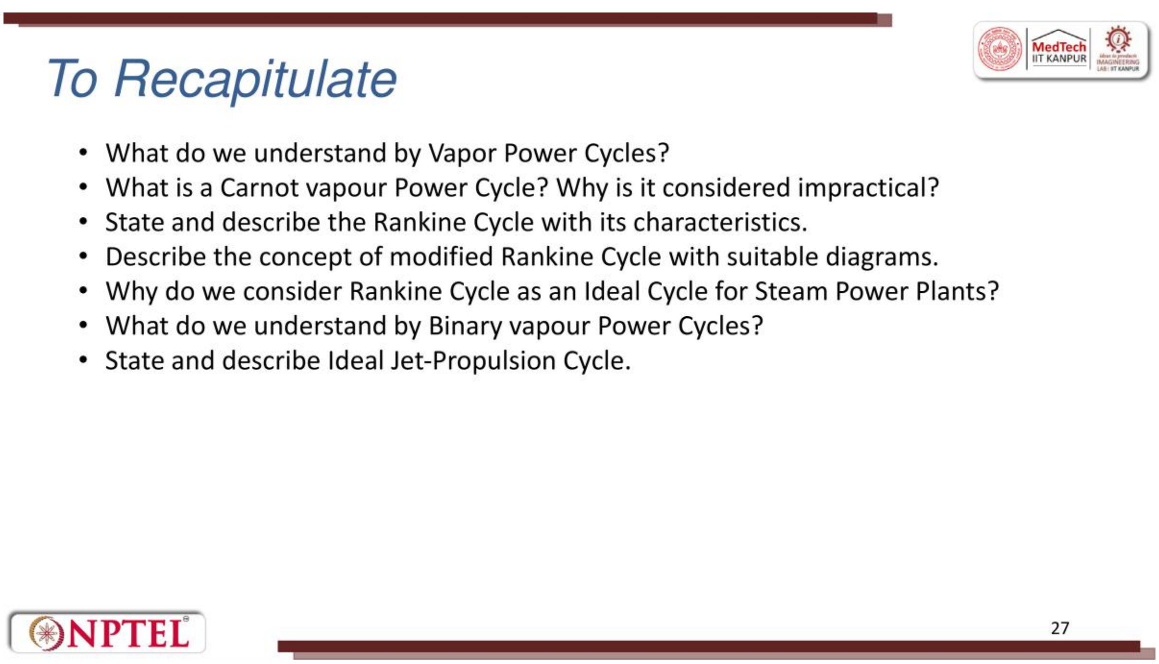


So, turboprop is a term which is generally used. The gas-turbine drives the compressor and the propeller. Turboprop, which is also part of an ideal jet propulsion cycle. Why am I covering all these things?

Because today, flight is something that fascinates you. I have been talking about the steam turbine. So now, what happens in a plane? If you know that, then you will enjoy it next time when you travel. So, a gas-turbine drives the compressor and the propeller.

Most of the thrust comes from the propeller. It works by accelerating a large volume of air to a moderate velocity. The propeller is best suited for low speeds, less than 500 miles per hour flights. The bypass ratio is 100 to 1 or more. The bypass ratio is the mass flow bypassing the combustion chamber divided by the mass flow through the combustion chamber.

So, these things are called turbo props. This is just an offset I have just mentioned. A compressor compresses the propeller, which propels and allows you to go. So, turbo prop engines are for very small flights. They used to have turbo prop engines.



So, in this lecture, we first saw what a Vapour Power Cycle is. Then we saw what the Carnot Vapour Power Cycle is. Why is it considered? Then we went into the Rankine cycle, then the modified Rankine cycle. Then, what are the considerations we had for the Rankine cycle as an ideal cycle for steam power plants? Binary Vapour Power Cycles.

What are jet propulsion cycles? And finally, we saw what the vapour compression refrigeration system is.

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These are the references we used in preparing the slides.

Thank you.