

# Basics of Mechanical Engineering-3

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Week 11

## Lecture 45: Basics of Nozzles

Welcome to the next lecture on nozzles. As you know, a nozzle will always have a taper like this. So, you will have an inlet and then an outlet, which we use in pipes. So, as you taper down, the area reduces, and you will see the velocity increases. So, that is how you pinch your hose pipe to increase the pressure and then start cleaning the car or vehicle. Whatever is the muddy portion, you try to do it on a scooter or so on and so forth. So, the nozzle is another major important part in fluid and thermal systems.

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### Contents

- Nozzles
- Types of nozzles
- Area velocity relationship
- Throttling process
- T-S diagram of throttling
- Mixing chamber
- Mass and Energy Conservation Equations during mixing



So, the content of this lecture will be nozzles, then different types of nozzles, area-velocity relationship, Throttling process, throttling is how you control the process, throttling process. Then a connection with our previously learned TS diagram of throttling. Then mixing chamber and finally mass and energy conservation equations during mixing.

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## Nozzles



- Nozzles are essential engineering devices designed to increase the velocity of a fluid at the expense of its pressure.
- They are commonly found in a wide range of applications, including jet engines, rockets, spacecraft and even ordinary garden hoses.
- **Conversely, devices that achieve the opposite task – increasing a fluid's pressure by slowing it down – are known as diffusers.**
- The study of fluid mechanics encompasses the analysis of these devices, particularly under high-speed, compressible flow conditions, where density changes become significant.



Nozzles are essential engineering devices, very important. So here, what happens is the velocity increases at the exit of the nozzle when the velocity increases at the expense of pressure. High pressure and high velocity is very difficult; high velocity and low pressure is okay. They are commonly found in a wide range of applications.

including jet engines, rockets, spacecraft, and even ordinary garden hose pipes, which I gave you as an example. If you want to sprinkle or if you want to water a farther distance, what we do is we always try to puncture or close the exit to make sure the water travels a longer distance. Conversely, devices that achieve the opposite task—increasing fluid pressure by slowing it down—are known as diffusers. So, this is a very important diffuser, right? The study of fluid mechanics encompasses the analysis of these devices, particularly under high-speed compressible flow conditions where density changes become significant.

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# Nozzles

The primary function of a nozzle is to accelerate a fluid. In practical terms, this acceleration is crucial for:

- **Propulsion systems:** Such as those found in jet engines and rockets, where high-velocity exhaust gases generate thrust.
- **Industrial processes:** Including industrial blasting and torch nozzles.
- **Power generation:** Nozzles are fundamental components in steam and gas turbines, where they convert fluid energy into kinetic energy to drive the turbine blades.



The primary function of a nozzle is to accelerate a fluid. So the exit, for example, if you have a nozzle like this. A nozzle like this. So this is a through hole. So depending upon the hole you make and the cone you design, you can control the spraying pattern.

You can see here; this is the field of view. You can see how it sprays. Over a large area. As the standoff increases, the spray area increases, forming a cone. This is very important.

So the nozzle is always used to accelerate fuel in practical terms. The acceleration is crucial for propulsion systems, industrial processes, and power generation. When we talk about propulsion systems, such as those found in jet engines and rockets, where high-velocity exhaust gases generate thrust.

Then industrial processes include industrial blasting and torch nozzles. Torch nozzles are used for painting, flame generation, water cleaning, and other things. Power generation is where nozzles are fundamental components in steam and gas turbines, where they convert fluid energy into kinetic energy to drive the turbine blades. Nozzles play a very important role.

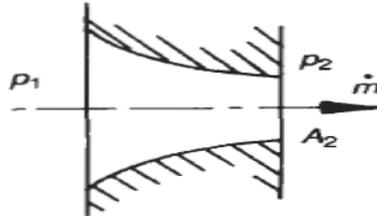
## Types of Nozzles



There are three primary types of nozzles:

### 1. Converging Nozzles:

- These nozzles have a cross-sectional area that decreases in the direction of flow.
- They are used to accelerate subsonic flows (Mach number  $< 1$ ).
- The maximum velocity a fluid can achieve in a converging nozzle is the sonic velocity (Mach number = 1), which occurs at the nozzle exit.



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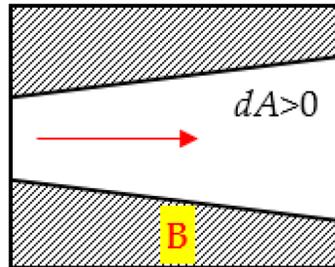
There are three different types of nozzles. They are converging nozzles, diverging nozzles, and converging-diverging nozzles. So let us go one after the other: converging nozzles. These nozzles have a cross-sectional area that decreases in the direction of flow, from where the flow happens. So the area is this. Okay. From the area, you can try to derive the diameter. So there is a reduction in the cross-sectional area in the flow direction. So here they are used to accelerate subsonic flow where the Mach number is less than 1.

The maximum velocity a fluid can achieve in a converging nozzle is the sonic velocity, where the Mach number = 1.

## Types of Nozzles

### 2. Diverging Nozzles:

- The cross-sectional area of these nozzles increases in the flow direction.
- They are used to accelerate supersonic flows (Mach number  $> 1$ ).

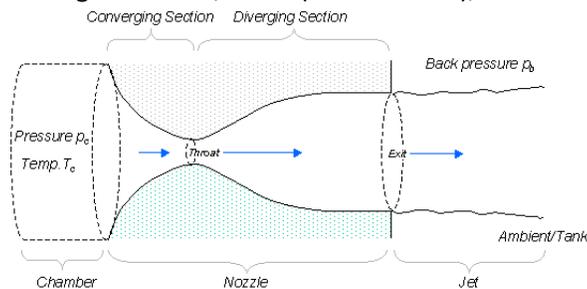


Let us go to diverging nozzles. Diverging nozzles are nozzles where there is an increase in the area or an increase in the diameter along the flow direction. So here, we will try to achieve supersonic flow, where the Mach number will always be greater than 1.

## Types of Nozzles

### 3. Converging–Diverging (Laval) Nozzles:

- These nozzles consist of a converging section followed by a diverging section, with a minimum flow area in between known as the throat.
- They are specifically designed to accelerate gases to supersonic speeds.
- This design allows a fluid to pass through subsonic, sonic (at the throat), and then supersonic velocities.
- The first successful use of such a nozzle was in a steam turbine designed by Carl G. B. de Laval in 1893.



So, when we try to put a combination of convergent-divergent nozzles, it converges from here and then diverges. So, it is called a converging-diverging nozzle or it is called a

Laval nozzle. These nozzles consist of a converging cross-section followed by a diverging section, with a minimum flow area in between the two, which is known as the throat. So, the throat—this area is called the throat. And here, the minimum flow area occurs between these two.

So, if you combine a convergent-divergent nozzle, you can divide it into several sections. The first section is called the chamber. The next section is called the nozzle. The third section is called the jet. So, these are the three sections.

And in the nozzle, you will have a converging section and diverging sections. Converging and diverging sections. When the jet exits, it enters the ambient or it can be an incubated tank where it is supposed to perform some other function. So they are specifically designed to accelerate gases to supersonic speeds.

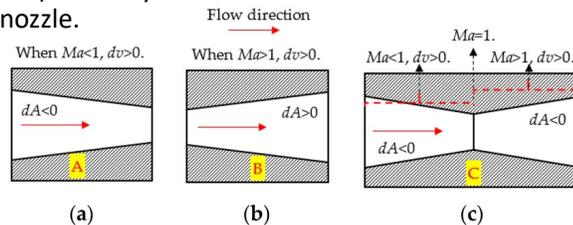
So if you go back, the converging is subsonic, and the diverging is supersonic. So here, convergent-divergent nozzles can also be designed to achieve supersonic speeds. This design allows a fluid to pass through subsonic, sonic, and then supersonic velocities. The first successful use of such a nozzle was in the steam turbine designed by Carl G. B. de Laval. So that is why it is called as Laval nozzles.

## Area-Velocity Relationship



The relationship between the flow area and velocity is fundamental in compressible flow through nozzles:

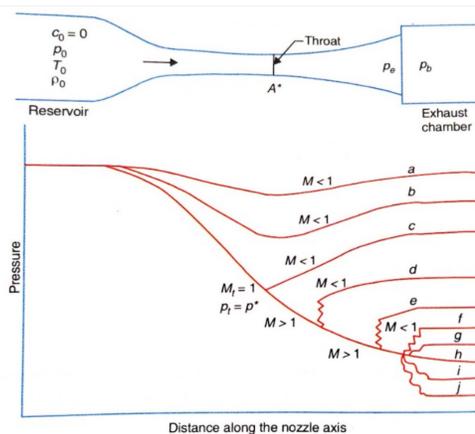
- For subsonic flow (Mach number  $< 1$ ), to increase velocity, the flow area must decrease (converging section).
- For supersonic flow (Mach number  $> 1$ ), to increase velocity, the flow area must increase (diverging section).
- The sonic velocity (Mach number = 1) can only occur at a location of minimum flow area, specifically the throat of the nozzle.



So the area-velocity relationship. The relationship between the flow area and the velocities is fundamental in compressible flows through nozzles. For subsonic flow, where the Mach number is less than 1, to increase velocity, the flow area must decrease.

For supersonic, where the Mach number should be greater than 1, to increase the velocity, the flow area must increase (diverging nozzle). A sonic velocity where Mach number equal to 1 can increase only occur at a local of minimum flow area especially or specifically in the throat of a nozzle. Throat of a nozzle is here where  $Ma$  equal to 1, ok. This is convergent; this is divergent.

## Area-Velocity Relationship



- The graphs shows the pressure changes along the axis of a convergent-divergent nozzle for different exit conditions.
- Illustrates how flow starts subsonic in the convergent section, reaches sonic speed at the throat, and can become supersonic in the divergent section, depending on pressure ratios.
- The graph lines (a-j) represent different flow regimes, highlighting critical features like the throat (minimum area, Mach 1) and the effects of back pressure.



The *graph* given here shows the pressure; the x-axis is pressure, and the y-axis is distance along the nozzle. The graph shows the pressure change along the axis of a convergent-divergent nozzle. This is a convergent-divergent nozzle with a throat in between. So,  $P_0$ ,  $T_0$ —that is rho, initial density, temperature, and pressure.

All these things are given here. When it exits out, it is at  $P_b$ ;  $P_e$  is the exit, and  $P_b$  is into the tank. The graph shows the pressure change along the axis of the convergent-divergent nozzle for different exit conditions.

You can see here the distance along the nozzle area. When you ascend, when you move, you see there the  $M$ , the graph—whatever it is—where we put a, b, c, d, e. You can see how the response is happening. This illustrates how the flow starts subsonic in the

beginning, in the convergent section, reaches sonic speed at the throat, and can become supersonic in the divergent side, depending on the pressure ratio.

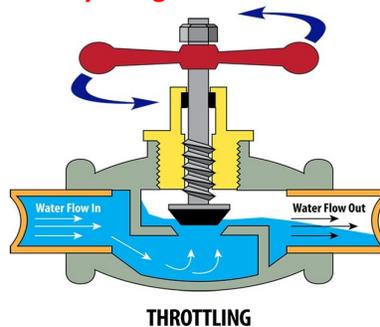
The graph from a to j represents different flow regimes, highlighting critical features like the throat where the minimum area Mach is 1 and the effect of back pressure. It just tries to show the relationship with respect to the effect of back pressure.

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## Throttling Process



- A throttling process involves the passage of a fluid through a flow-restricting device, such ability to cause a substantial pressure drop.
- Common examples include adjustable valves, capillary tubes, or porous plugs.
- **This process is central to many refrigeration and air conditioning units function.**



<https://www.plumbingsupply.com/images/compression-valve-throttling.jpg>

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Throttling process. Throttle. Throttle is somebody dictating. The throttling process means you are trying to open or close the valve so that the fluid flow or gas flow can happen. In your house, the burner uses a throttle to open and close the gas flow to the burner.

The throttling process involves the passage of a fluid. Through a flow-restricting device, such as the ability to cause a substantial pressure drop, this is achieved by the throttling process. Common examples of the throttling process include adjusting valves, capillary tubes, or porous plugs. So you plug and then unplug it. The process is central to many refrigeration and air conditioning unit functions.

# Throttling Process

Throttling devices are widely employed in practice.

Familiar instances include:

- Ordinary adjustable valves.
- Capillary tubes, often used in refrigeration and air conditioning applications.
- Porous plugs.
- The expansion valve in refrigerators:
- Refrigerant-134a enters the capillary tube as a saturated liquid and is throttled to a lower pressure, causing a rapid temperature drop.

Throttling devices are widely used in practice. Familiar instances include ordinary adjustable valves, taps, capillary tubes often used in refrigerators and air conditioning applications, porous plugs, and the expansion valve in refrigerators. The refrigerant 134A enters the capillary tube as a saturated liquid and is throttled to a lower temperature, causing a rapid temperature drop.

# Enthalpy Before and After Throttling

- Given the typical assumptions (adiabatic, no work, negligible kinetic and potential energy changes), the conservation of energy equation for a single-stream steady-flow device simplifies significantly.
- This means that the enthalpy values at the inlet and exit of a throttling valve are approximately the same.
- Therefore, a throttling valve is sometimes referred to as an isenthalpic device.
- This constant enthalpy property means that the final outcome of a throttling process depends on how the internal energy and flow energy interact.



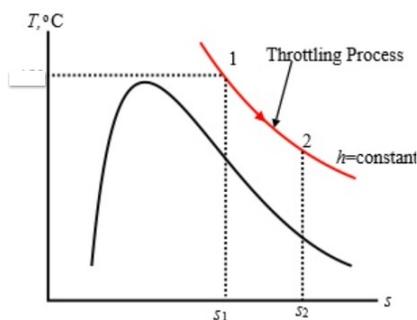
So, what happens to the enthalpy before and after throttling? Given typical assumptions: adiabatic, no work. Negligible kinetic and potential energy changes. The conservation of

energy equation for a single-stream, steady-flow device simplifies significantly. These are very important assumptions, whatever we made: adiabatic, no work, negligible kinetic and potential energy changes. The energy equation for a single steady-state flow device simplifies significantly.

This means that the enthalpy values at the inlet and exit of the throttling valve are approximately the same. Therefore, a throttling valve is sometimes referred to as an isenthalpic device. So this is very important. When or why is it called an isenthalpic device? This constant enthalpy property means that the final outcome of a throttling process depends on how the internal energy and the flow energy interact with each other. This is very important.

This constant enthalpy property means that the final outcome, so you can see here, there is  $p_1V_1$ , which is passing through the porous one, here you get  $p_2V_2$ . So, here again  $p_1V_1$ , we try to push it to the porous, we get  $p_2V_2$ . So, the constant enthalpy property means that the final outcome of a throttling process depends on how the internal energy and the flow energy interact.

## Enthalpy Before and After Throttling



- During throttling, a fluid (like steam or gas) passes through a narrow valve or restriction, causing its pressure to drop suddenly. Even though the pressure drops, the total energy content related to heat and work (called enthalpy) stays the same before and after the valve.
- So, enthalpy before throttling = enthalpy after throttling, but the pressure is lower after the valve. This means the fluid loses pressure without gaining or losing heat or doing any work.

During the throttling process, a fluid passes through a narrow valve or restriction, causing it pressure to drop suddenly. So, it passes through a narrow valve, then there is a sudden pressure drop. So, this is the TS diagram. You can see here the throttling process is

happening. Even though the pressure drops, the total energy content related to heat and work stays the same before and after the valve. So, this is very important and is called enthalpy. Before and after the valve, it is the same.

So, enthalpy before throttling equals enthalpy after throttling, but the pressure is lower after the valve. This means the fluid loses pressure without gaining or losing heat or doing any work. So, this is very important. The enthalpy before the throttle and after the throttle is the same.

Because here we say that even though the pressure drops, the total energy content related to the heat and the work stays the same before and after the valve. So that leads to enthalpy before throttling and after throttling being the same. So this means the fluid loses pressure without gaining or losing heat or doing any work.

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## *Pressure Drop while Throttling*

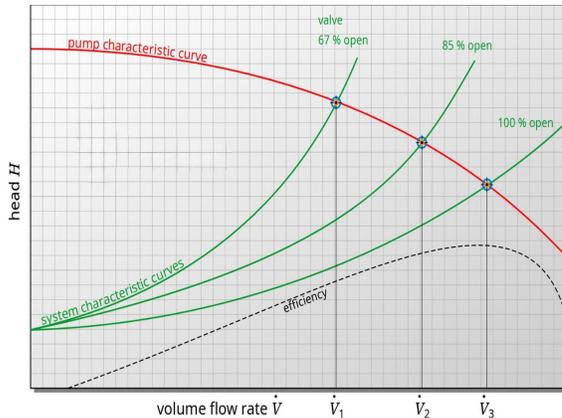


- One of the most defining characteristics of throttling is that it achieves a significant pressure drop without involving any work interaction.
- Unlike a turbine, which extracts work from the fluid as its pressure drops, a throttling device dissipates the pressure energy primarily into increased kinetic energy (which is then often dissipated) or internal energy, rather than converting it into useful work.
- This is why the control volume energy equation for a throttling valve often reduces to enthalpy being constant.

The pressure drop while throttling—one of the most defining characteristics of throttling—is that it achieves a significant pressure drop without involving any work interaction. Pressure drop happens by closing and opening; the pressure drop occurs without involving work interaction. Unlike turbines, which extract work from the fluid as the pressure drops. In a turbine, as and when you hit it, the pressure drops, which extracts work from the fluid as the pressure decreases.

The throttling device dissipates the pressure energy primarily into increased kinetic energy or internal energy rather than converting it into useful work. So, this is again, friends, very important. This is why the control volume energy equation for a throttling valve often reduces to enthalpy being constant.

## Pressure Drop while Throttling



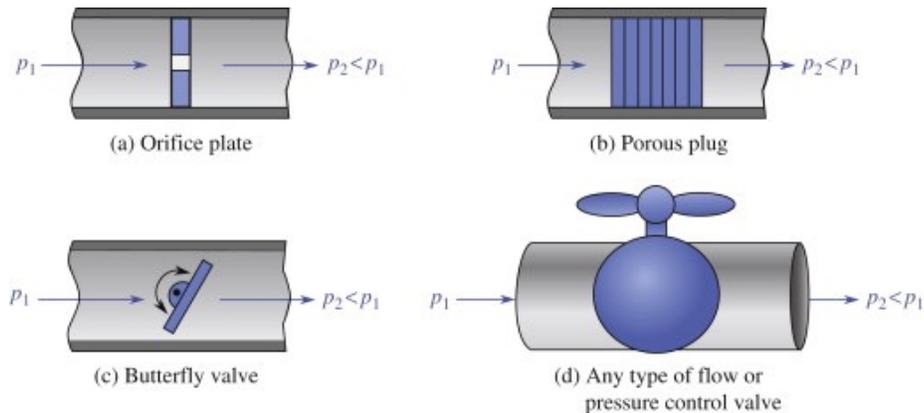
- Shows how the flow rate and head (pressure) in a piping system change as a valve throttles (partially closes).
- Throttling the valve reduces flow and the pressure drop across the valve (the system curve shifts upward), meaning the pump needs to work against a higher resistance.
- Different curves for "valve 67%, 85%, 100% open" illustrate how closing the valve increases the pressure drop for the same flow rate.



So, here we can see the graph between  $H$  and the volume flow rate. Volume flow rate is  $\dot{V}$ . So, you have  $V_1$ ,  $V_2$ ,  $V_3$ ,  $V_4$ , and you can see the pump characteristics—how it falls down—and here are the system characteristic curves when the valve is 67 percent open, 85 percent open, and when the valve is 100 percent open. So, you can mark these points and drop them to find out the  $V_1$ ,  $V_2$ , and  $V_3$  volume flow rates.

This figure shows the flow rate and the head in a piping system, which changes as the valve throttle position changes. Throttling the valve—this is throttling the valve—reduces flow and the pressure drop across the valve, meaning the pump needs to work against higher resistance. Different curves for the valve at 67%, 87%, and 100% open illustrate how throttling the valve increases the pressure drop at the same flow rate. Whatever happens, you can see here how the efficiency falls down. So, the efficiency reaches its maximum at 100%.

## Pressure Drop while Throttling



So, the pressure drop while throttling can occur due to an orifice plate, a porous plug, a butterfly valve, or any type of flow or pressure control valve. So, in orifice flow, you have pressure  $p_1$  on one side and  $p_2$  on the other. So, you can see that  $p_2$  is greater than  $p_1$ . So, there is a pressure drop that happens through the orifice. So, here, there is a porous media pressure drop. Then, there is a butterfly valve. Depending on the valve opening,  $p_2$  and  $p_1$  change. And then here, it is any type of flow. So here, it is like a throttle valve. You open the thing, you get the same thing.  $P_2$  is greater than  $P_1$ .

## Throttling vs. Isentropic Expansion

It is important to distinguish throttling from isentropic expansion:

- Throttling is an irreversible process because it involves fluid friction and other dissipative effects. On a T-S diagram, this irreversibility means that entropy increases during throttling.
- Isentropic expansion, in contrast, is an idealized, reversible process where entropy remains constant.
- If the throttling device in a refrigeration cycle were replaced by an isentropic turbine, the refrigerant would enter the evaporator at a lower enthalpy and higher pressure, potentially increasing refrigeration capacity and decreasing net work input.

So, if we want to compare throttling versus isentropic expansion, it is important to distinguish throttling from isentropic expansion. Throttling is an irreversible process. Because it involves fluid friction and other dissipating effects on a TS diagram.

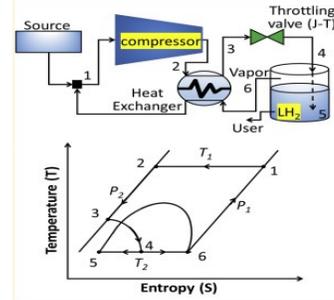
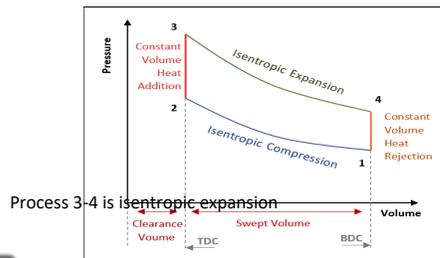
This irreversibility means the entropy increases during throttling. Isentropic expansion, in contrast, is an idealized reversible process where entropy remains constant. So, please understand the difference between these two. Throttling is an irreversible process because there can be friction loss, fluid friction, and dissipating effects. Isentropy, in contrast, is an idealized reversible process where entropy remains constant.

If the throttling device in a refrigeration cycle were replaced by isentropic turbine, the refrigerant would enter the evaporator at a lower enthalpy and higher pressure, potentially increasing refrigeration capacity and decreasing the net work in the input. So, if we replace the throttling device, then what will happen is discussed in this paragraph.

## Throttling vs. Isentropic Expansion



- While an isentropic expansion would theoretically improve efficiency, replacing the throttling valve with an isentropic turbine is often impractical due to the added cost and complexity, making the throttling valve a more economical and simple choice for most refrigeration applications.



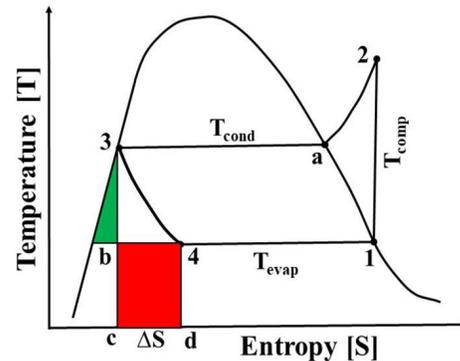
So, while an isentropic expansion would theoretically improve efficiency, replacing the throttling valve with an isentropic turbine is often impractical due to additional cost and complexity. So, this is how you get the isentropic expansion, which is given in the PV diagram. So you can see here pressure versus swept volume clearance volume. You have 1, where in which there is a compression happening 2, then there it the pressure increases

but constant volume heat addition happens. From 3 you go back to 4, where it is isentropic expansion. So, the constant volume heat rejection happens from 4 to 1. So, it is isentropic compression and isentropic expansion happening here. So, this is a process: 3 to 4 is isentropic expansion. And the process 3 to 4, if it is replaced by a throttle, then it looks like this.

## T–S Diagram of Throttling



- On a T-S (temperature-entropy) diagram, a throttling process is typically represented by a line of constant enthalpy, moving from a higher pressure to a lower pressure.
- Due to its irreversible nature, the process results in an increase in entropy.
- The process line on a T-s diagram for throttling usually moves downwards and to the right, indicating a drop in temperature (if  $\mu > 0$ ) and an increase in entropy.



The TS diagram looks like this. So, it starts from 1. It goes to 2, 2 to 3, 3 jumps to 4, 4 to 5, then it goes to 6, 6 to 1. It is a little complex, so you see here, if you want to do the process 3 to 4, then we have a source here, a heat exchanger here, then the heat exchanger gets its input from the compressor. So, 1 goes here, then goes to the heat exchanger, then whatever happens in the heat exchanger, from the heat exchanger it goes to 3, 3 to the throttle valve, throttle valve to the tank where you can store this. So, if you see 1 to 2, there is a compression, right? And then 1 to 2, then 2 to 3, 2 to 3 is the heat exchanger. So, there is a temperature decrease in the heat exchanger from 2 to 3.

So, at 3 it decreases when it goes to 3, there is a throttle valve. So, it goes to 4. So, 4 gets into a user tank, so it comes here, and whatever heat is getting rejected, it has to go as an evaporator and it comes to 6. So, the TS diagram: on the TS diagram, you can see the temperature entropy diagram; a throttling process is typically represented by a line of

constant enthalpy. Moving from higher pressure to lower pressure. Higher pressure to lower pressure, it is moving, right?

Due to its irreversible nature, the process results in an increase in entropy. So, you can see here: 1, 2, right? The temperature increases, compression happens. Then, 2 to A, then 2 to 3, where the temperature is constant. Entropy reduces. Then, 3 to 4, the temperature falls down, and 4 to 1, it goes here. So, if you see the C, C, D, B, this area. This area is red, and you have a green area.

So, on the TS diagram, your throttle process is typically represented by a constant enthalpy line moving from a higher pressure to a lower pressure. Due to its irreversible nature, the throttling process results in an increase in entropy. The process line on a TS diagram for throttling usually moves downward to the right, indicating the drop in temperature and an increase in entropy.

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## Importance of Throttling



- The throttling process is crucial for refrigeration and air conditioning cycles.
- In a vapor-compression refrigeration cycle, the high-pressure, saturated liquid refrigerant from the condenser is passed through a throttling device (e.g., a capillary tube or expansion valve).
- This causes a drastic drop in both pressure and temperature of the refrigerant.
- **The resulting low-temperature, low-pressure mixture then enters the evaporator, where it absorbs heat from the refrigerated space, providing the cooling effect.**

So, why is throttling very important? The throttling process is crucial for air conditioning and refrigeration cycles. In the vapor compression refrigeration cycle, the high-pressure saturated liquid refrigerant from the condenser is passed through the throttling device. So, there is an expansion that happens. This causes a drastic drop in both pressure and temperature. This results in a low-temperature, low-pressure mixture, which then enters

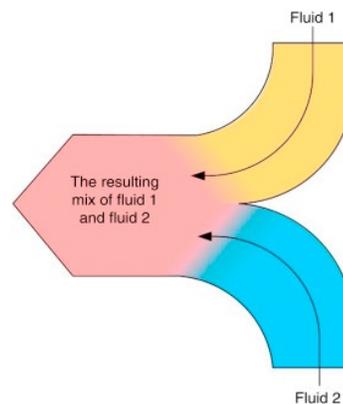
the evaporator where it absorbs heat from the refrigerated space, providing a cooling effect. So, this is important. Why and how does a cooling effect happen? The low temperature, low pressure mixing then enters the evaporator, where it absorbs from the refrigerator cycle.

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## Mixing Chambers



- A mixing chamber is a section or device in engineering applications where two or more streams of fluids are combined to form a single stream.
- This process is common and essential in various systems, often without requiring a distinct, specially designed chamber.
- For instance, an ordinary T-elbow or a Y-elbow in a shower can serve as a mixing chamber for cold and hot water streams.
- Mixing chambers are sometimes also classified as direct-contact heat exchangers.



Mixing chambers are the other important thing because there can be water mixed with some other oil or water mixed with an abrasive. So there is mixing between two colors or mixing between two refrigerants. So the mixing chamber is also very important. So you will have a fluid 1 coming, fluid 2 coming and these 2 come and get mixed here in this chamber.

A mixing chamber is a section or a device in engineering applications where two or more streams of fluid are combined to form a single stream. The process is common and essential in various systems, often without requiring a distinct, especially during designed chambers. For instance, an ordinary T-elbow or a Y-elbow in a shower is also used for mixing. That is true.

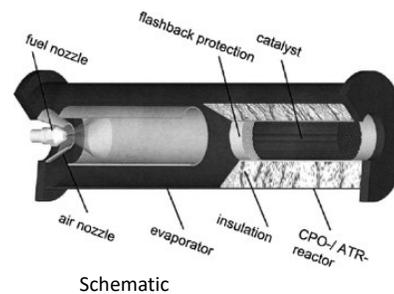
You can have hot water coming. You can have cold water coming. These two get mixed in the mixing fluid. So, for instance, an ordinary T-elbow or a Y-elbow in the shower can serve as a mixing chamber for cold and hot water streams. The mixing chamber is sometimes classified as a direct-contact heat exchanger.

## Mixing Chambers



For simplified analysis, mixing chambers are typically modelled under several key assumptions:

- **Steady-Flow Process:** It is assumed that there is no change with time at any point within the control volume of the mixing chamber. This implies that the mass and energy contents of the control volume remain constant.
- **Adiabatic (No Heat Loss):** Mixing chambers are generally considered well-insulated, meaning that heat losses to the surroundings are negligible, so heat transfer ( $\dot{Q}$ ) is approximately zero.



So there are the mixing chambers for simplified analysis. Mixing chambers are typically modeled under several key assumptions. Steady flow process and adiabatic process. Steady flow process: it is assumed that there is no change with time at any point within the control volume of the mixing chamber. There is no change with time at any point within the control volume of the mixing chamber.

This implies that the mass and energy content of the control volume remains constant. This is very important, as it implies that the mass and energy content of the control volume remains constant in a steady flow process. When we talk about adiabatic, where there is no heat loss, the mixing chambers are generally considered well insulated, meaning that the heat loss to the surroundings is negligible.

So, when the mixing chambers are generally considered well insulated for adiabatic processes, meaning that the heat losses to the surroundings are negligible. So, you can see here. This is a fuel nozzle, so you can have an air nozzle, then it has an evaporator which,

on top or behind it, has insulation. So, mixing chambers are generally considered well insulated, meaning the heat loss to the surroundings is negligible. You put a pipe and then surround it with thermocol insulation. So, there is no heat transfer called  $Q$ .

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## To Recapitulate



- What are Nozzles?
- Enlist and state various types of nozzles.
- How does throttling process occur?
- Write short notes on mixing chamber.



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With this, friends, we have seen some basics of a nozzle. Then we have enlisted and seen various types of nozzles. We saw what a throttling process is and what the significance of a mixing chamber is.

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## Reference



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These are some of the references which we have been using in preparing these lecture notes.

And thank you very much.