GENERAL PHYSICS PH1110

Nam Le, Dr.

School of Engineering Physics

Hanoi University of Science and Technology

2. THERMODYNAMICS

2.2 FIRST LAW OF THERMODYNAMICS

1. Statement of the first law

1. Statement of the first law

- The law was stated by **Rudolf Clausius** in 1850.

1. Statement of the first law

- The law was stated by **Rudolf Clausius** in 1850.

> The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

1. Statement of the first law

- The law was stated by **Rudolf Clausius** in 1850.

> The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W}$$

1. Statement of the first law

- The law was stated by **Rudolf Clausius** in 1850.

The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \quad \text{or} \quad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

1. Statement of the first law

♣ The law was stated by **Rudolf Clausius** in 1850.

The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \qquad \text{or} \qquad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

- The change, $\Delta U = U_{\text{final}} - U_{\text{initial}}$,

1. Statement of the first law

♣ The law was stated by **Rudolf Clausius** in 1850.

The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \qquad \text{or} \qquad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

- The change, $\Delta U = U_{\text{final}} - U_{\text{initial}}$, is the same as the increase in internal energy.

1. Statement of the first law

♣ The law was stated by **Rudolf Clausius** in 1850.

The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \qquad \text{or} \qquad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

- The change, $\Delta U = U_{\text{final}} - U_{\text{initial}}$, is the same as the increase in internal energy.
- If Q' is the heat transferred from the system

1. Statement of the first law

♣ The law was stated by **Rudolf Clausius** in 1850.

> The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \qquad \text{or} \qquad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

- The change, $\Delta U = U_{\text{final}} - U_{\text{initial}}$, is the same as the increase in internal energy.
- If Q' is the heat transferred from the system and W' is the work done by the system:

1. Statement of the first law

- The law was stated by **Rudolf Clausius** in 1850.

> The change in internal energy of a system is equal to the heat added to the system plus the work done on the system.

$$\boxed{\Delta U = Q + W} \qquad \text{or} \qquad \boxed{\mathrm{d}U = \delta Q + \delta W}$$

- The change, $\Delta U = U_{\text{final}} - U_{\text{initial}}$, is the same as the increase in internal energy.
- If Q' is the heat transferred from the system and W' is the work done by the system:

$$\boxed{\Delta U + Q' + W' = 0}$$

2. THERMODYNAMICS

2.2 FIRST LAW OF THERMODYNAMICS

2. Work and heat in equilibrium processes

2. Work and heat in equilibrium processes

♣ **Equilibrium states**

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas,

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS.

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS. If N is fixed, only two of them are independent.

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS. If N is fixed, only two of them are independent.
- In case p and V are chosen as independent variables,

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS. If N is fixed, only two of them are independent.
- In case p and V are chosen as independent variables, each state is represented by a point in the **PV diagram**.

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS. If N is fixed, only two of them are independent.
- In case p and V are chosen as independent variables, each state is represented by a point in the **PV diagram**. However, we can only represent equilibrium states.

2. Work and heat in equilibrium processes

♣ Equilibrium states

- For an ideal gas, the variables N, p, V, and T are related by the EOS. If N is fixed, only two of them are independent.
- In case p and V are chosen as independent variables, each state is represented by a point in the **PV diagram**. However, we can only represent equilibrium states.

Each variable has a single value in an equilibrium state, and its change between any two equilibrium states is single-valued.

2. Work and heat in equilibrium processes

- **Equilibrium processes**

2. Work and heat in equilibrium processes

♣ **Equilibrium processes**

An equilibrium process is a series of equilibrium states.

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process)

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.
- Work done in an equilibrium process (quasi-static work):

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.
- Work done in an equilibrium process (quasi-static work):

$$\boxed{\mathrm{d}W = -p\mathrm{d}V}$$

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.
- Work done in an equilibrium process (quasi-static work):

$$\boxed{\mathrm{d}W = -p\mathrm{d}V} \quad \rightarrow \quad W = -\int_{\widehat{12}} p\mathrm{d}V$$

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.
- Work done in an equilibrium process (quasi-static work):

$$\boxed{\mathrm{d}W = -p\mathrm{d}V} \quad \rightarrow \quad W = -\int_{\overset{\frown}{12}} p\mathrm{d}V \quad \text{(path dependent)}$$

2. Work and heat in equilibrium processes

♣ Equilibrium processes

An equilibrium process is a series of equilibrium states.

- Each equilibrium process is represented by a curve segment in the PV diagram.
- In practice, a quasi-static process (a sufficiently slow process) can be considered as an equilibrium process.
- Work done in an equilibrium process (quasi-static work):

$$\boxed{\mathrm{d}W = -p\mathrm{d}V} \quad \rightarrow \quad W = -\int_{\widehat{12}} p\mathrm{d}V \quad \text{(path dependent)}$$

This work is equal to the area under the pV curve.

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overline{1a2b1}} p\,\mathrm{d}V$$

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overline{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p \mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T$$

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overline{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\widehat{12}} \frac{m}{\mu}C\mathrm{d}T$$

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\overparen{12}} \frac{m}{\mu}C\mathrm{d}T$$

where c is the **specific heat capacity**

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overline{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\widehat{12}} \frac{m}{\mu}C\mathrm{d}T$$

where c is the **specific heat capacity** and C is the **molar heat capacity**.

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overline{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\widehat{12}} \frac{m}{\mu}C\mathrm{d}T$$

where c is the **specific heat capacity** and C is the **molar heat capacity**. The heat Q is path dependent.

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\overparen{12}} \frac{m}{\mu}C\mathrm{d}T$$

  where c is the **specific heat capacity** and C is the **molar heat capacity**. The heat Q is path dependent.

- Definition of molar heat capacity:

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\overparen{12}} \frac{m}{\mu}C\mathrm{d}T$$

  where c is the **specific heat capacity** and C is the **molar heat capacity**. The heat Q is path dependent.

- Definition of molar heat capacity:

$$C \equiv \frac{\mu}{m}\frac{\delta Q}{\mathrm{d}T}$$

2. Work and heat in equilibrium processes

- Work done in an equilibrium cycle (closed process):

$$W = -\int_{\overparen{1a2b1}} p\mathrm{d}V = \text{area limited by the path}$$

- Heat added to the system can be written in the form

$$\delta Q = mc\mathrm{d}T = \frac{m}{\mu}C\mathrm{d}T \qquad \rightarrow \qquad Q = \int_{\overparen{12}} \frac{m}{\mu}C\mathrm{d}T$$

  where c is the **specific heat capacity** and C is the **molar heat capacity**. The heat Q is path dependent.

- Definition of molar heat capacity:

$$C \equiv \frac{\mu}{m}\frac{\delta Q}{\mathrm{d}T} \qquad \rightarrow \qquad \boxed{C = \frac{\mu}{m}\frac{\partial Q}{\partial T}}$$

2. THERMODYNAMICS

2.2 FIRST LAW OF THERMODYNAMICS

3. Equilibrium processes of ideal gases

3. Equilibrium processes of ideal gases

- **Isochoric process**

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation:

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$

- Work:

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$
- Heat:

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$
- Heat: $$Q = \Delta U$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$

- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$

- Heat: $$Q = \Delta U \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\frac{i}{2}R\Delta T}$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$
- Heat: $$Q = \Delta U \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\frac{i}{2}R\Delta T}$$
- Molar heat capacity at constant volume:

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$

- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$

- Heat: $$Q = \Delta U \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\frac{i}{2}R\Delta T}$$

- Molar heat capacity at constant volume:

$$C_{\mathrm{V}} = \frac{\mu}{m}\left(\frac{\partial Q}{\partial T}\right)_V$$

3. Equilibrium processes of ideal gases

♣ **Isochoric process** (constant-volume process, V = constant)

- Equation: $$\boxed{\frac{p}{T} = \text{constant}}$$
- Work: $$W = \int \mathrm{d}W = -\int p\,\mathrm{d}V \quad \rightarrow \quad \boxed{W = 0}$$
- Heat: $$Q = \Delta U \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\frac{i}{2}R\Delta T}$$
- Molar heat capacity at constant volume: $$C_V = \frac{\mu}{m}\left(\frac{\partial Q}{\partial T}\right)_V \quad \rightarrow \quad \boxed{C_V = \frac{i}{2}R}$$

3. Equilibrium processes of ideal gases

- ♣ **Isobaric process**

3. Equilibrium processes of ideal gases

- **Isobaric process** (constant-pressure process, p = constant)

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation:

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, $p = \text{constant}$)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

- Work:

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, $p = \text{constant}$)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p \int \mathrm{d}V$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation:

$$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p \int \mathrm{d}V = -p\Delta V$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p \int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu} R\Delta T}$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p\int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu}R\Delta T}$

- Heat:

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation:

$$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p\int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu}R\Delta T}$

- Heat: $Q = \Delta U - W$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$
- Work: $W = -p\int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu}R\Delta T}$
- Heat: $Q = \Delta U - W \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\left(\frac{i}{2}+1\right)R\Delta T}$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, $p =$ constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$
- Work: $W = -p\int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu}R\Delta T}$
- Heat: $Q = \Delta U - W \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\left(\frac{i}{2}+1\right)R\Delta T}$
- Molar heat capacity at constant pressure:

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$

- Work: $W = -p \int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu} R \Delta T}$

- Heat: $Q = \Delta U - W \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\left(\frac{i}{2} + 1\right) R \Delta T}$

- Molar heat capacity at constant pressure:

$$C_\mathrm{p} = \frac{\mu}{m}\left(\frac{\partial Q}{\partial T}\right)_p$$

3. Equilibrium processes of ideal gases

♣ **Isobaric process** (constant-pressure process, p = constant)

- Equation: $$\boxed{\frac{V}{T} = \text{constant}}$$
- Work: $W = -p\int \mathrm{d}V = -p\Delta V \quad \rightarrow \quad \boxed{W = -\frac{m}{\mu}R\Delta T}$
- Heat: $Q = \Delta U - W \quad \rightarrow \quad \boxed{Q = \frac{m}{\mu}\left(\frac{i}{2}+1\right)R\Delta T}$
- Molar heat capacity at constant pressure:

$$C_\mathrm{p} = \frac{\mu}{m}\left(\frac{\partial Q}{\partial T}\right)_p \quad \rightarrow \quad \boxed{C_\mathrm{p} = \frac{i+2}{2}R}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio**

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

$$\boxed{\gamma = \frac{C_p}{C_V}}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition: $$\boxed{\gamma = \frac{C_p}{C_V}}$$

- For ideal gases:

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

$$\boxed{\gamma = \frac{C_{\mathrm{p}}}{C_{\mathrm{V}}}}$$

- For ideal gases:

$$\boxed{C_{\mathrm{V}} = \frac{i}{2}R} \qquad \boxed{C_{\mathrm{p}} = \frac{i+2}{2}R}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

$$\boxed{\gamma = \frac{C_\mathrm{p}}{C_\mathrm{V}}}$$

- For ideal gases:

$$\boxed{C_\mathrm{V} = \frac{i}{2}R} \qquad \boxed{C_\mathrm{p} = \frac{i+2}{2}R} \qquad \rightarrow \qquad \boxed{\gamma = \frac{i+2}{i}}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

$$\boxed{\gamma = \frac{C_\mathrm{p}}{C_\mathrm{V}}}$$

- For ideal gases:

$$\boxed{C_\mathrm{V} = \frac{i}{2}R} \qquad \boxed{C_\mathrm{p} = \frac{i+2}{2}R} \qquad \rightarrow \qquad \boxed{\gamma = \frac{i+2}{i}}$$

$$i = \frac{2}{\gamma - 1}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition: $$\boxed{\gamma = \frac{C_p}{C_V}}$$

- For ideal gases:

$$\boxed{C_V = \frac{i}{2}R} \qquad \boxed{C_p = \frac{i+2}{2}R} \qquad \rightarrow \qquad \boxed{\gamma = \frac{i+2}{i}}$$

$$i = \frac{2}{\gamma - 1} \qquad \rightarrow \qquad \boxed{C_V = \frac{R}{\gamma - 1}}$$

3. Equilibrium processes of ideal gases

♣ **Heat capacity ratio** (adiabatic index)

- Definition:

$$\boxed{\gamma = \frac{C_\mathrm{p}}{C_\mathrm{V}}}$$

- For ideal gases:

$$\boxed{C_\mathrm{V} = \frac{i}{2}R} \qquad \boxed{C_\mathrm{p} = \frac{i+2}{2}R} \qquad \rightarrow \qquad \boxed{\gamma = \frac{i+2}{i}}$$

$$i = \frac{2}{\gamma - 1} \qquad \rightarrow \qquad \boxed{C_\mathrm{V} = \frac{R}{\gamma - 1}} \qquad \boxed{C_\mathrm{p} = \frac{\gamma R}{\gamma - 1}}$$

3. Equilibrium processes of ideal gases

♣ **Isothermal process**

3. Equilibrium processes of ideal gases

- **Isothermal process** (constant-temperature, T = constant)

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation:

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work:

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$
- Work: $W = -\int_{\widehat{12}} p\mathrm{d}V$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $$W = -\int_{\widehat{12}} p\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $$W = -\int_{\widehat{12}} p\,\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$$

$$W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2}$$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$
- Work: $W = -\int_{\widehat{12}} p\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$

$$\boxed{W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2} = \frac{m}{\mu}RT\ln\frac{p_2}{p_1}}$$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $$W = -\int_{\widehat{12}} p\,\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$$

$$\boxed{W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2} = \frac{m}{\mu}RT\ln\frac{p_2}{p_1}}$$

- Heat:

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$
- Work: $W = -\int_{\widehat{12}} p\,\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$

$$\boxed{W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2} = \frac{m}{\mu}RT\ln\frac{p_2}{p_1}}$$

- Heat: $\Delta T = 0$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $$W = -\int_{\widehat{12}} p\,\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$$

$$\boxed{W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2} = \frac{m}{\mu}RT\ln\frac{p_2}{p_1}}$$

- Heat: $\Delta T = 0 \quad \rightarrow \quad \Delta U = 0$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $W = -\int_{\widehat{12}} p\mathrm{d}V = -\frac{m}{\mu}RT\int_{V_1}^{V_2}\frac{\mathrm{d}V}{V}$

$$\boxed{W = \frac{m}{\mu}RT\ln\frac{V_1}{V_2} = \frac{m}{\mu}RT\ln\frac{p_2}{p_1}}$$

- Heat: $\Delta T = 0 \quad \rightarrow \quad \Delta U = 0 \quad \rightarrow \quad Q = -A.$

3. Equilibrium processes of ideal gases

♣ **Isothermal process** (constant-temperature, T = constant)

- Equation: $\boxed{pV = \text{constant}}$

- Work: $$W = -\int_{\widehat{12}} p\,\mathrm{d}V = -\frac{m}{\mu} RT \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V}$$

$$\boxed{W = \frac{m}{\mu} RT \ln \frac{V_1}{V_2} = \frac{m}{\mu} RT \ln \frac{p_2}{p_1}}$$

- Heat: $\Delta T = 0 \quad \to \quad \Delta U = 0 \quad \to \quad Q = -A.$

$$\boxed{Q = \frac{m}{\mu} RT \ln \frac{V_2}{V_1} = \frac{m}{\mu} RT \ln \frac{p_1}{p_2}}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process**

3. Equilibrium processes of ideal gases

- **Adiabatic process** (no heat transferred, $Q = 0$)

3. Equilibrium processes of ideal gases

- **Adiabatic process** (no heat transferred, $Q = 0$)
  - Equation:

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

<u>and</u> $\qquad \delta W = -p\mathrm{d}V$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

$$\underline{\text{and}} \qquad \delta W = -p\mathrm{d}V \quad \rightarrow \quad \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V) = -p\mathrm{d}V$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

<u>and</u> $\delta W = -p\mathrm{d}V \quad \rightarrow \quad \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V) = -p\mathrm{d}V$

$$\frac{\mathrm{d}p}{p} + \gamma\frac{\mathrm{d}V}{V} = 0$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

<u>and</u> $$\delta W = -p\mathrm{d}V \quad \rightarrow \quad \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V) = -p\mathrm{d}V$$

$$\frac{\mathrm{d}p}{p} + \gamma\frac{\mathrm{d}V}{V} = 0 \quad \rightarrow \quad \boxed{pV^{\gamma} = \text{constant}}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

<u>and</u> $$\delta W = -p\mathrm{d}V \quad \rightarrow \quad \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V) = -p\mathrm{d}V$$

$$\frac{\mathrm{d}p}{p} + \gamma\frac{\mathrm{d}V}{V} = 0 \quad \rightarrow \quad \boxed{pV^{\gamma} = \text{constant}}$$

- The PV diagram of an adiabatic process is similar to that of an isothermal process,

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Equation:

$$\delta Q = 0 \quad \rightarrow \quad \delta W = \mathrm{d}U = \frac{m}{\mu}\frac{i}{2}R\mathrm{d}T = \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V)$$

$$\underline{\text{and}} \qquad \delta W = -p\mathrm{d}V \quad \rightarrow \quad \frac{1}{\gamma - 1}(\mathrm{d}pV + p\mathrm{d}V) = -p\mathrm{d}V$$

$$\frac{\mathrm{d}p}{p} + \gamma\frac{\mathrm{d}V}{V} = 0 \quad \rightarrow \quad \boxed{pV^{\gamma} = \text{constant}}$$

- The PV diagram of an adiabatic process is similar to that of an isothermal process, but the magnitude of its gradient is greater.

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\,\mathrm{d}V$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p \mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\,\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

$$\frac{pV}{\gamma - 1}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p \mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

$$\frac{pV}{\gamma - 1} = pV \frac{C_V}{R}$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

$$\frac{pV}{\gamma - 1} = pV\frac{C_{\mathrm{V}}}{R} = C_{\mathrm{V}}\frac{m}{\mu}T$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^{\gamma} \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^{\gamma}} = -p_1 V_1^{\gamma} \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

$$\frac{pV}{\gamma - 1} = pV\frac{C_V}{R} = C_V \frac{m}{\mu} T$$

$$W = \frac{m}{\mu} C_V (T_2 - T_1)$$

3. Equilibrium processes of ideal gases

♣ **Adiabatic process** (no heat transferred, $Q = 0$)

- Work:

$$W = -\int_{\widehat{12}} p\mathrm{d}V = -p_1 V_1^\gamma \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V^\gamma} = -p_1 V_1^\gamma \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1}$$

$$\boxed{W = \frac{p_2 V_2 - p_1 V_1}{\gamma - 1}}$$

In terms of change in temperature:

$$\frac{pV}{\gamma - 1} = pV\frac{C_\mathrm{V}}{R} = C_\mathrm{V}\frac{m}{\mu}T$$

$$\boxed{W = \frac{m}{\mu}C_\mathrm{V}(T_2 - T_1) = \frac{m}{\mu}C_\mathrm{V}\Delta T}$$