II. Energy and the First Law of Thermodynamics

A. Energy Transfer by Work. Energy is Conserved.

1. Energy can cross the boundary of a closed system by only two mechanisms: heat transfer and work transfer.

2. The change in energy of a closed system is equal to the net heat transferred to the system minus the net work performed by the system.

\[
\Delta E_{total} = \Delta E_{system} + \Delta E_{surroundings} = 0
\]

\[
\Delta E_{system} = -\Delta E_{surroundings}
\]

\[
\Delta E_{sys} = Q_{in,net} + W_{in,net}
\]

Net work in, \( W_{in,net} = W_{in} - W_{out} \)

Closed system

Net heat in, \( Q_{in,net} = Q_{in} - Q_{out} \)

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B. Mechanical work and power

1. Introduction

a. Work done by force \( F \) on a body displaced distance \( s \) is

\[
W = Fs \text{ (kJ)}
\]

\[
W = \int F \, ds \text{ (kJ)}
\]

\((2-22)\)

b. Power supplied to body moving with velocity \( V \):

\[
W = FV \text{ (kW)}
\]
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c. Work and heat are processes, not properties. Work and heat are represented as areas on a graph. E, e, V, T, P, m are properties and are represented by points on a graph.

d. Work and heat are also known as path functions.

\[ \int_{1}^{2} dE = E_2 - E_1 = \Delta E \] (any path between states 1, 2)
\[ \oint dE = 0 \text{ or } \oint dV = 0 \] (any cycle)
\[ \int_{1}^{2} \delta W = W_{12} \] (not \( \Delta W \))

- Shaded area = \(-\int_{\text{cycle}} \delta W_{\text{in}} = -W_{\text{in,net}} \)

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2. Expansion and compression work

a. Transfer of energy to a system by boundary work requires that a force act on the boundary and that the boundary move.

b. Differential work done on the system is, for a piston of area A,

\[ \delta W_{b,\text{in}} = -F \, ds = -PA \, ds = -P \, dV \]

c. Replacing F with PA is strictly correct only for a quasi-equilibrium (reversible) process.

d. The boundary work done on system is minus the area under curve

\[ W_{b,\text{in}} = -\int_{V_1}^{V_2} P \, dV \] (4-2)
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3. Evaluation of integral

\[ W_{b,in} = -\int_{V_1}^{V_2} P \, dV \]

Remember that this equation only applies to a quasi-equilibrium (reversible) process.

How can we evaluate this integral? We look at three examples:
- \( P \) may be constant (see Example 4-2).
- \( P \) may be defined by ideal gas law for an isothermal process (see Example 4-3).
- Process may be polytropic (Section 4-1).

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3. Evaluation of integral. **Example** - Air is contained in a piston-cylinder device at 500 kPa at an initial volume of 0.040 m\(^3\). The air expands to a final volume of 0.075 m\(^3\). Calculate the work output under conditions of (a) constant pressure, (b) constant temperature.

<table>
<thead>
<tr>
<th>Data</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_1 = 0.040 ) m(^3)</td>
<td>1) Closed system.</td>
</tr>
<tr>
<td>( V_2 = 0.075 ) m(^3)</td>
<td>2) Quasi-equilibrium process.</td>
</tr>
<tr>
<td>( P_1 = 500 ) kPa</td>
<td>3) Ideal gas: ( PV = mRT )</td>
</tr>
</tbody>
</table>

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3. Example (cont.)

(a) Analysis (constant pressure)

\[ W_{\text{out}} = \int_{V_1}^{V_2} PdV = P(V_2 - V_1) \]

\[ W_{\text{out}} = 500 \text{ kPa} \left(0.075 - 0.040\right) m^3 = 18 \text{ kJ} \]

(b) Analysis (constant temperature)

\[ W_{\text{out}} = \int_{V_1}^{V_2} PdV = \int_{V_1}^{V_2} \frac{mRT}{V}dV = mRT \int_{V_1}^{V_2} \frac{dV}{V} \]

\[ W_{\text{out}} = mRT \ln \left(\frac{V_2}{V_1}\right) = P_V \ln \left(\frac{V_2}{V_1}\right) \]

\[ W_{\text{out}} = 500 \text{ kPa} \left(0.04 m^3\right) \ln \left(\frac{75}{40}\right) = 13 \text{ kJ} \]

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4. Polytropic process (Section 4-1 of text)

Many compression and expansion processes can be modeled as polytropic processes. The boundary work for such a process can be calculated as follows, where \( n \) is typically 1.2 or 1.3.

\[ PV^n = C \text{ or } P = CV^{-n} \]

\[ W_{\text{out}} = \int_{V_1}^{V_2} PdV \]

\[ W_{\text{out}} = C \int_{V_1}^{V_2} V^{-n}dV = C \left. \frac{V^{1-n}}{1-n} \right|_{V_1}^{V_2} = \frac{P_2V_2 - P_1V_1}{1-n}, \quad n \neq 1 \quad (4-9) \]

For an ideal gas, \( PV = mRT \) and

\[ W_{b,\text{out}} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n}, \quad n \neq 1 \quad (4-10) \]

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