Thermodynamics: An Engineering Approach, 6th Edition
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Chapter 8
EXERGY: A MEASURE OF WORK POTENTIAL

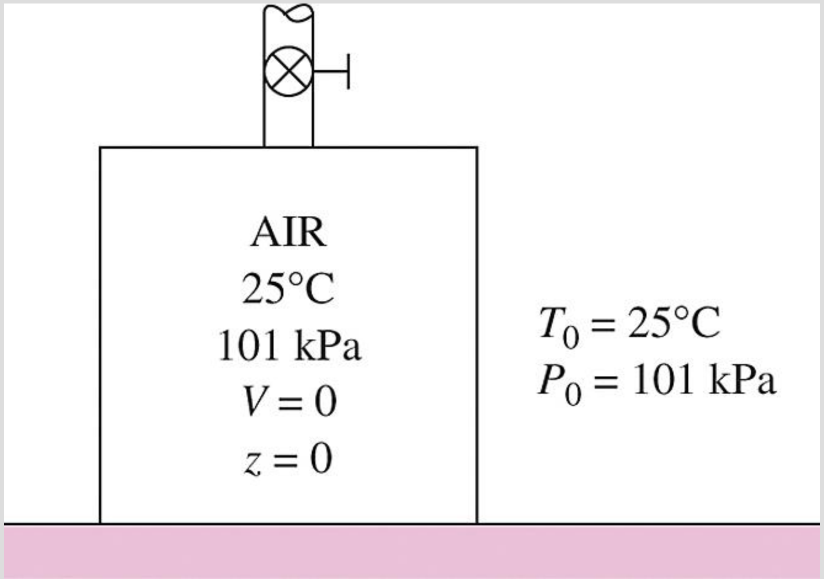
Objectives

- Examine the performance of engineering devices in light of the second law of thermodynamics.
- Define *exergy*, which is the maximum useful work that could be obtained from the system at a given state in a specified environment.
- Define *reversible work*, which is the maximum useful work that can be obtained as a system undergoes a process between two specified states.
- Define the exergy destruction, which is the wasted work potential during a process as a result of irreversibilities.
- Define the *second-law efficiency*.
- Develop the exergy balance relation.
- Apply exergy balance to closed systems and control volumes.

EXERGY: WORK POTENTIAL OF ENERGY

The useful work potential of a given amount of energy at some specified state is called *exergy*, which is also called the *availability* or *available energy*.

A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment it is in.



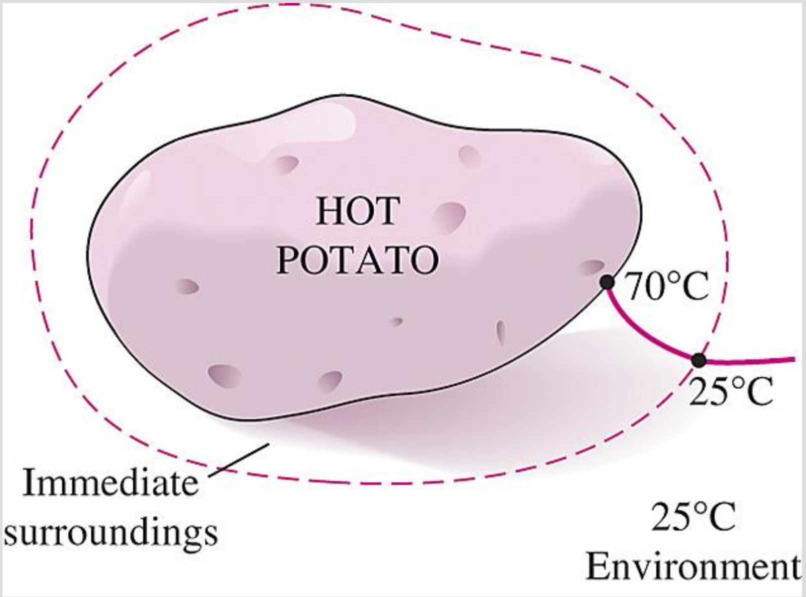
A system that is in equilibrium with its environment is said to be at the dead state.

At the dead state, the useful work potential (exergy) of a system is zero.

A *system delivers the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its environment, that is, the dead state*.

This represents the *useful work potential* of the system at the specified state and is called exergy.

Exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.



The immediate surroundings of a hot potato are simply the temperature gradient zone of the air next to the potato.

The atmosphere contains a tremendous amount of energy, but no exergy.

Exergy (Work Potential) Associated with Kinetic and Potential Energy

Exergy of kinetic energy:

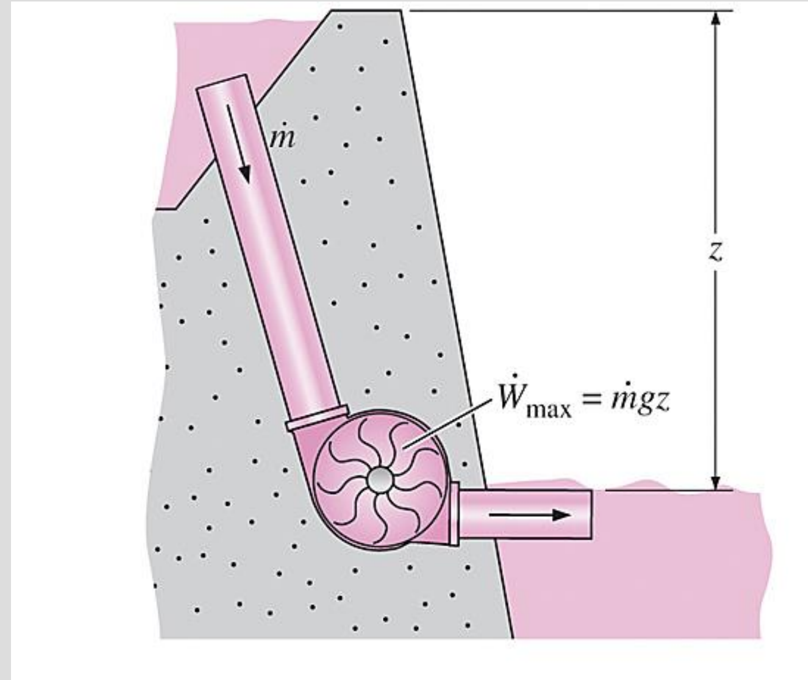
$$x_{pe} = pe = gz \qquad (kJ/kg)$$

Exergy of potential energy:

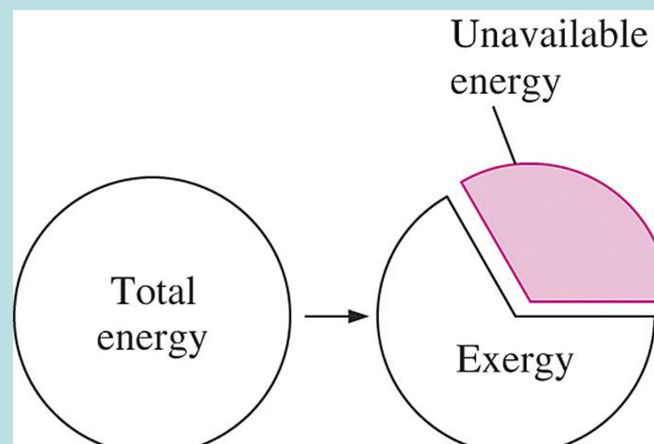
$$x_{ke} = ke = \frac{V^2}{2} \qquad (kJ/kg)$$

The exergies of kinetic and potential energies are equal to themselves, and they are entirely available for work.

The *work potential* or *exergy* of potential energy is equal to the potential energy itself.



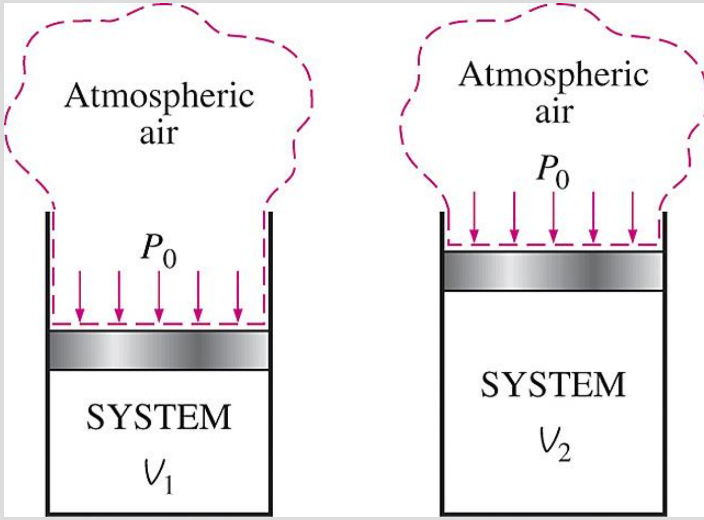
Unavailable energy is the portion of energy that cannot be converted to work by even a reversible heat engine.



REVERSIBLE WORK AND IRREVERSIBILITY

$$W_{surr} = P_0(V_2 - V_1)$$

$$W_u = W - W_{surr} = W - P_0(V_2 - V_1)$$

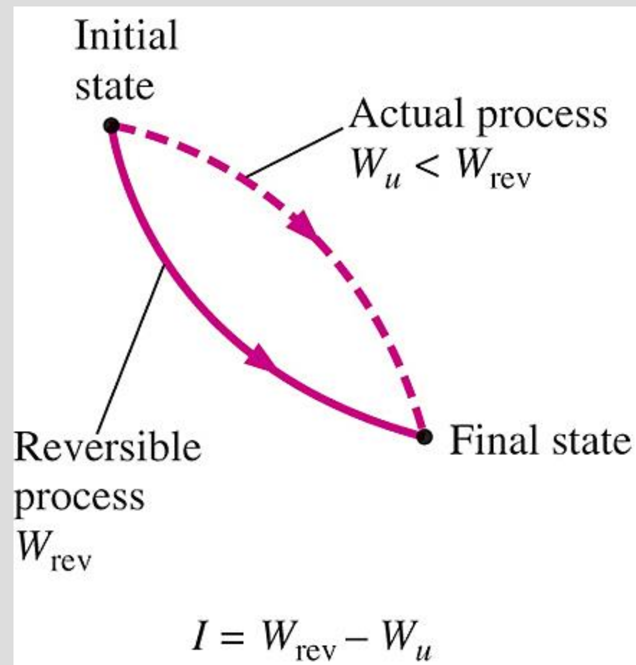


As a closed system expands, some work needs to be done to push the atmospheric air out of the way (W_{surr}).

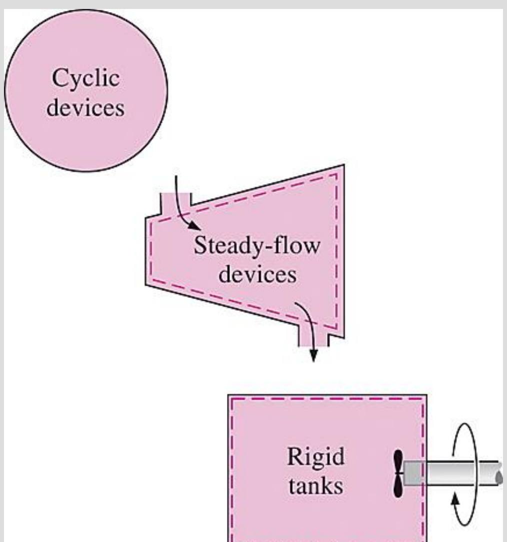
Reversible work W_{rev}: *The maximum amount of useful work that can be produced (or the minimum work that needs to be supplied) as a system undergoes a process between the specified initial and final states.*

$$I = W_{rev,out} - W_{u,out}$$

$$I = W_{u,in} - W_{rev,in}$$



The difference between reversible work and actual useful work is the irreversibility.



For constant-volume systems, the total actual and useful works are identical ($W_u = W$).

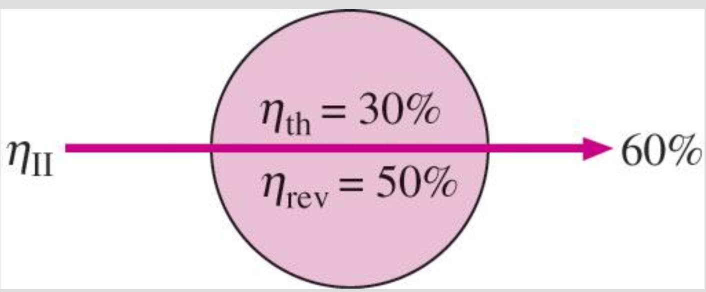
SECOND-LAW EFFICIENCY, η_{II}

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \qquad \text{(heat engines)}$$

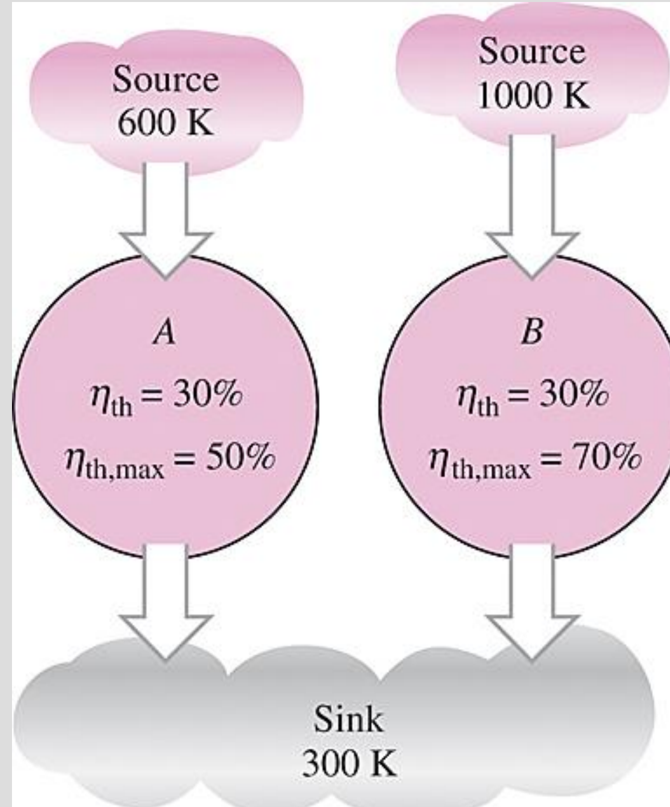
$$\eta_{II} = \frac{W_u}{W_{rev}} \qquad \text{(work-producing devices)}$$

$$\eta_{II} = \frac{W_{rev}}{W_u} \qquad \text{(work-consuming devices)}$$

$$\eta_{II} = \frac{\text{COP}}{\text{COP}_{rev}} \qquad \text{(refrigerators and heat pumps)}$$



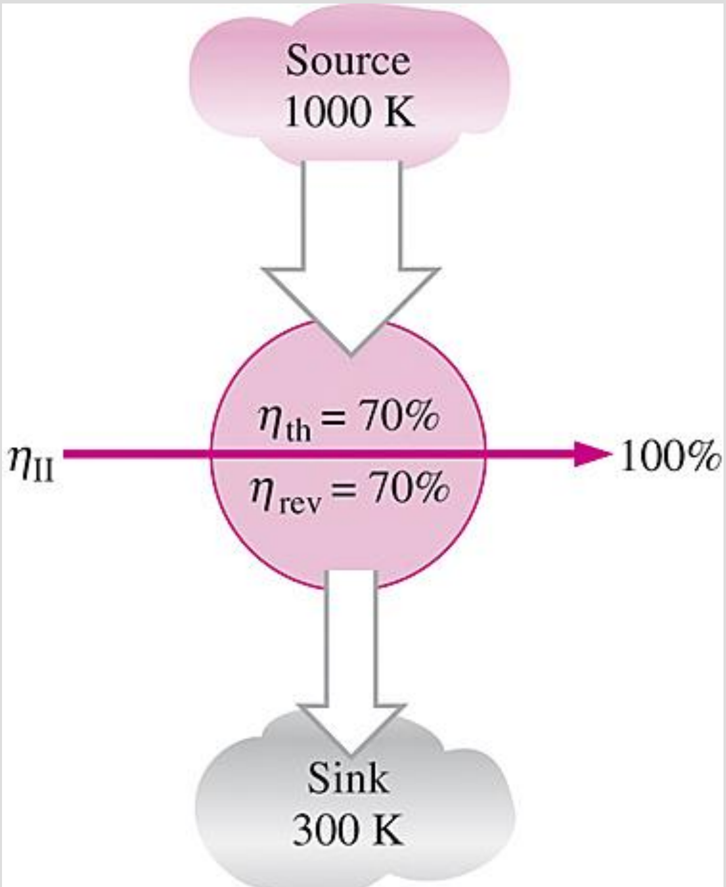
Second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions.



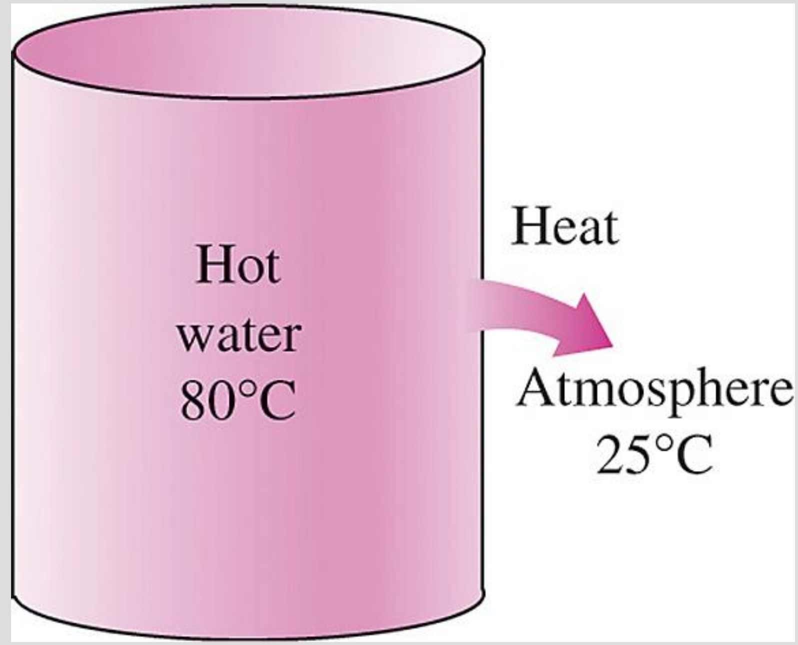
Two heat engines that have the same thermal efficiency, but different maximum thermal efficiencies.

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy supplied}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy supplied}}$$

General definition of exergy efficiency



Second-law efficiency of all reversible devices is 100%.



The second-law efficiency of naturally occurring processes is zero if none of the work potential is recovered.

EXERGY CHANGE OF A SYSTEM

Exergy of a Fixed Mass: Nonflow (or Closed System) Exergy

$$\underbrace{\delta E_{in} - \delta E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

$$-\delta Q - \delta W = dU$$

$$\delta W = P\,dV = (P - P_0)\,dV + P_0\,dV = \delta W_{b,\text{useful}} + P_0\,dV$$

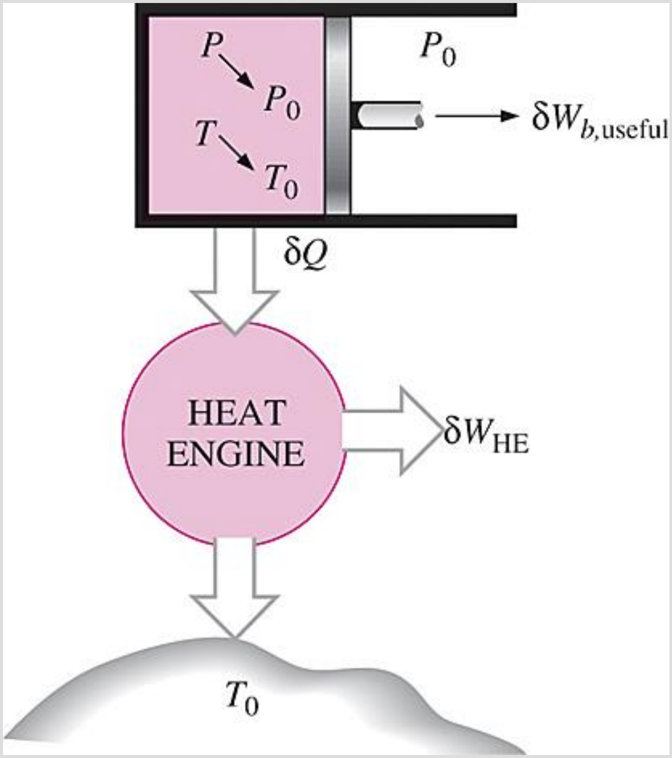
$$\delta W_{HE} = \left(1 - \frac{T_0}{T}\right)\delta Q = \delta Q - \frac{T_0}{T}\delta Q = \delta Q - (-T_0\,dS) \rightarrow$$

$$\delta Q = \delta W_{HE} - T_0\,dS$$

$$\delta W_{\text{total useful}} = \delta W_{HE} + \delta W_{b,\text{useful}} = -dU - P_0\,dV + T_0\,dS$$

$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + m\frac{V^2}{2} + mgz$$

Exergy of a closed system



The *exergy* of a specified mass at a specified state is the useful work that can be produced as the mass undergoes a reversible process to the state of the environment.

$$\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$
$$= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)$$

Closed system exergy per unit mass

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1) = (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$
$$= (U_2 - U_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1) + m\frac{V_2^2 - V_1^2}{2} + mg(z_2 - z_1)$$

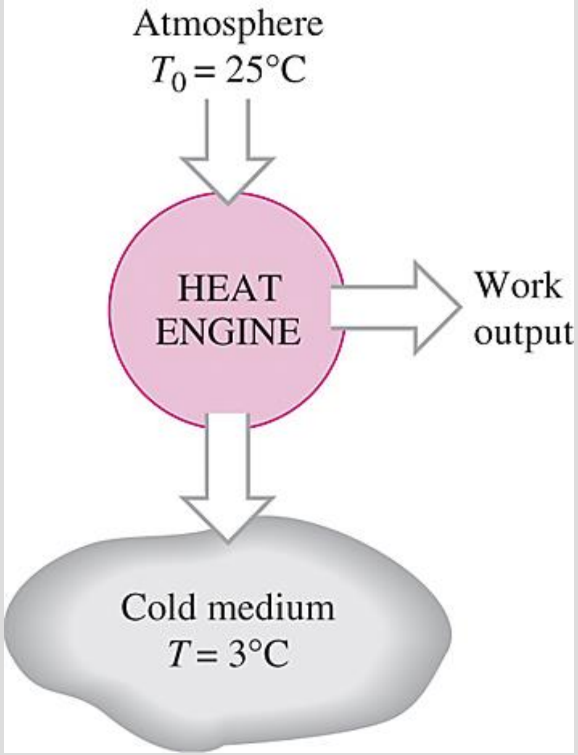
$$\Delta\phi = \phi_2 - \phi_1 = (u_2 - u_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$
$$= (e_2 - e_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1)$$

Exergy change of a closed system

When the properties of a system are not uniform, the exergy of the system is

$$X_{\text{system}} = \int \phi\, \delta m = \int_V \phi \rho\, dV$$

The *exergy* of a cold medium is also a *positive* quantity since work can be produced by transferring heat to it.



Exergy of a Flow Stream: Flow (or Stream) Exergy

$$x_{\text{flowing fluid}} = x_{\text{nonflowing fluid}} + x_{\text{flow}}$$

$$= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz + (P - P_0)v$$

$$= (u + Pv) - (u_0 + P_0 v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$= (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

Exergy of flow energy

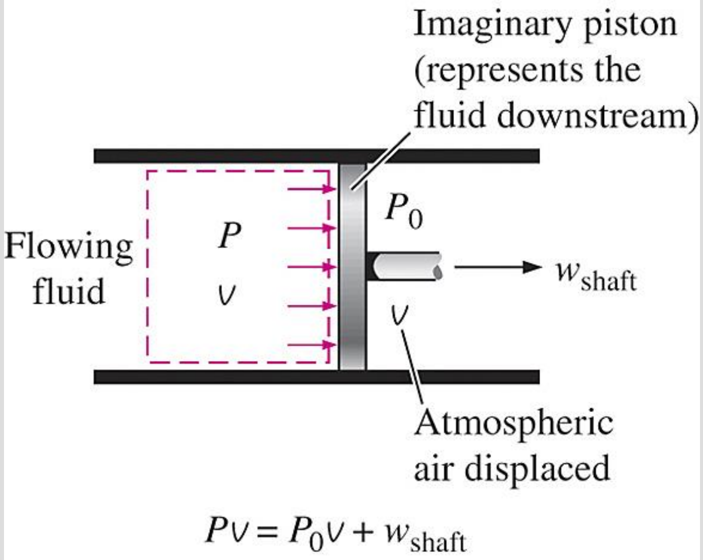
$$x_{\text{flow}} = Pv - P_0 v = (P - P_0)v$$

Flow exergy

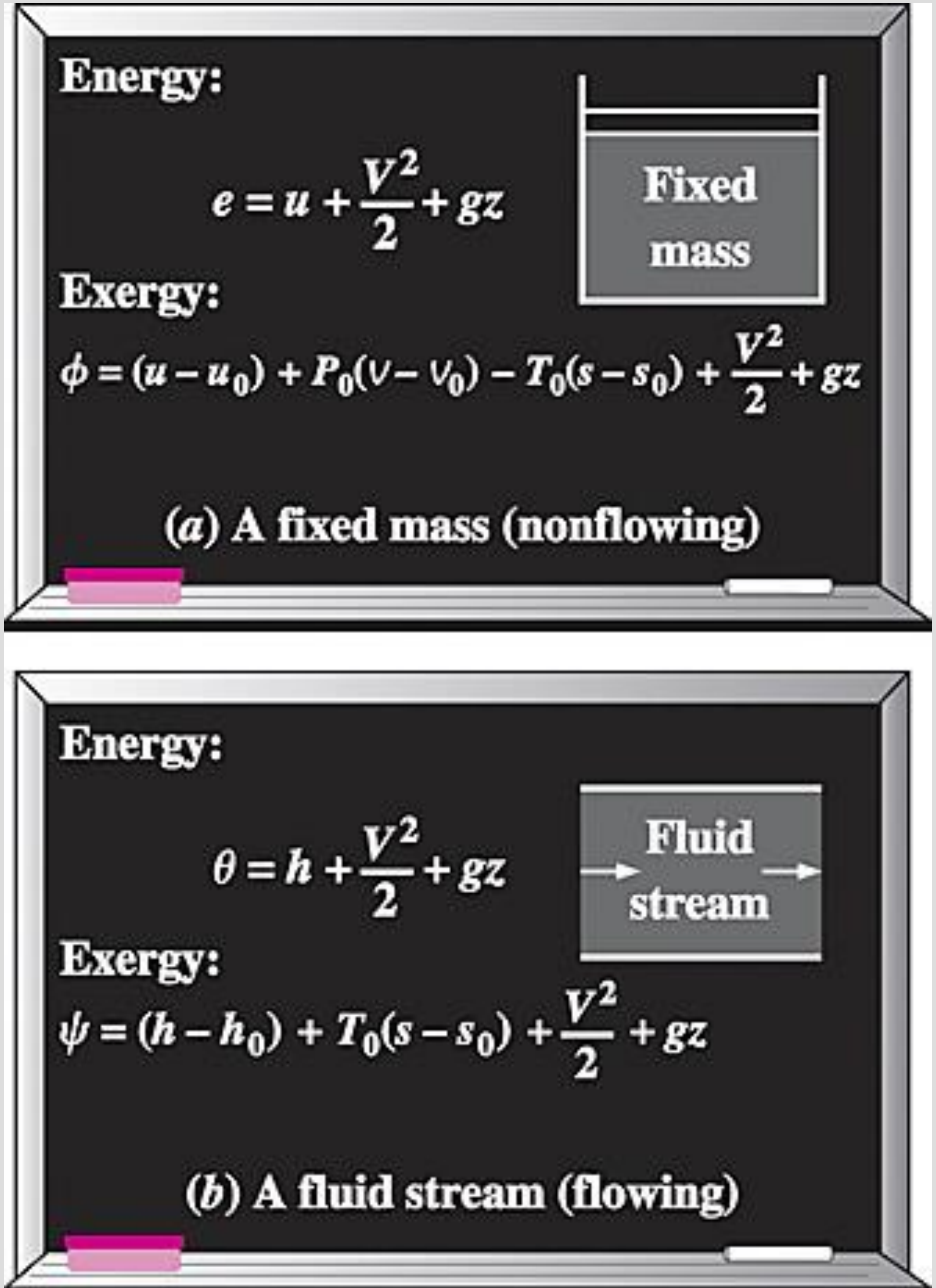
$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

Exergy change of flow

$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) + T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$



The *exergy* associated with *flow energy* is the useful work that would be delivered by an imaginary piston in the flow section.



The *energy* and *exergy* contents of
(*a*) a fixed mass
(*b*) a fluid stream.

EXERGY TRANSFER BY HEAT, WORK, AND MASS

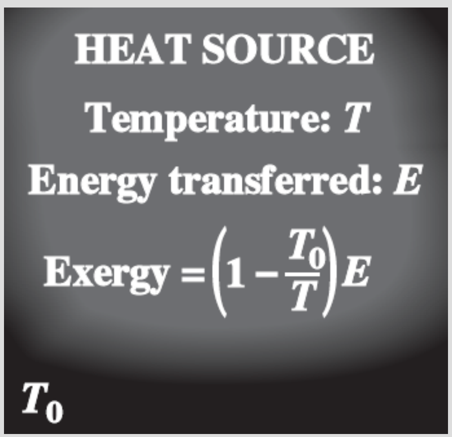
Exergy by Heat Transfer, *Q*

$$X_{\text{heat}} = \left(1 - \frac{T_0}{T}\right)Q$$

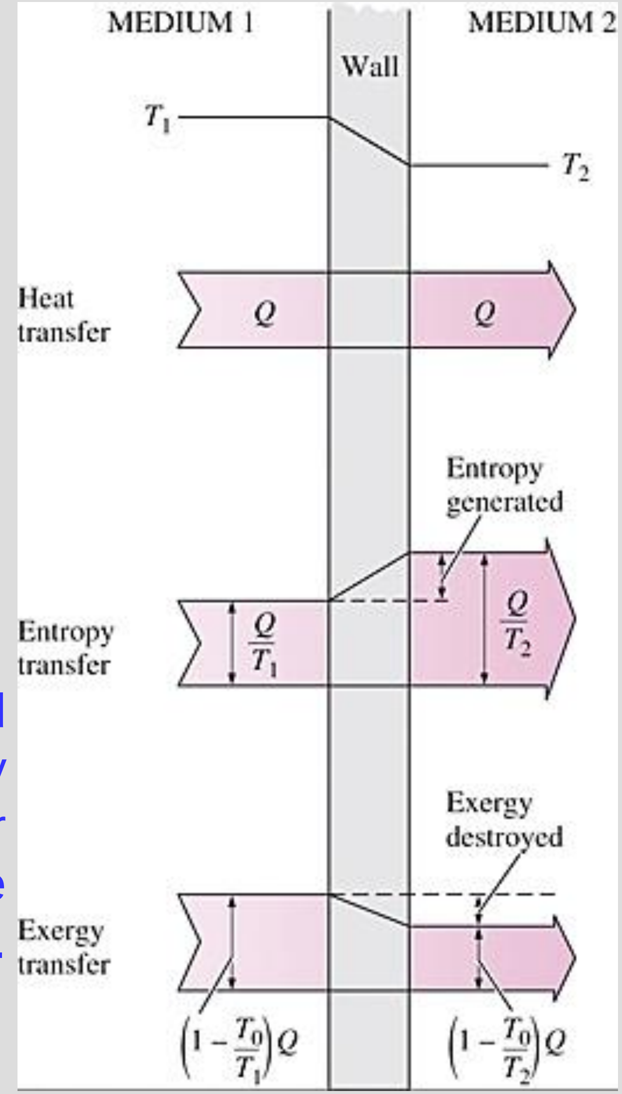
Exergy transfer by heat

$$X_{\text{heat}} = \int \left(1 - \frac{T_0}{T}\right) \delta Q$$

When temperature is not constant



The transfer and destruction of exergy during a heat transfer process through a finite temperature difference.

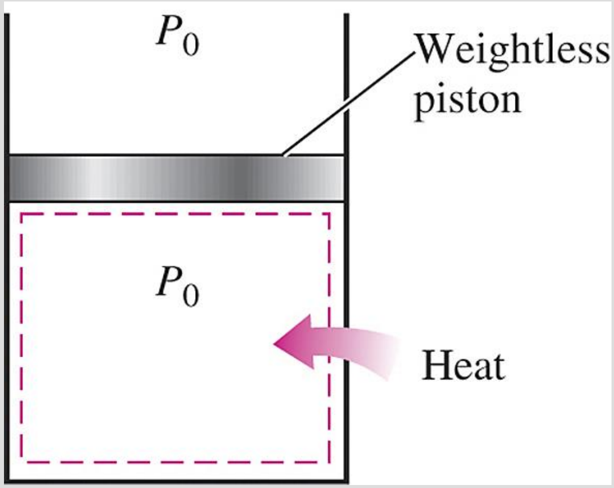


The Carnot efficiency $\eta_c = 1 - T_0/T$ represents the fraction of the energy transferred from a heat source at temperature T that can be converted to work in an environment at temperature T_0.

Exergy Transfer by Work, *W*

$$X_{work} = \begin{cases} W - W_{surr} & \text{(for boundary work)} \\ W & \text{(for other forms of work)} \end{cases}$$

$$W_{surr} = P_0(V_2 - V_1)$$



There is no useful work transfer associated with boundary work when the pressure of the system is maintained constant at atmospheric pressure.

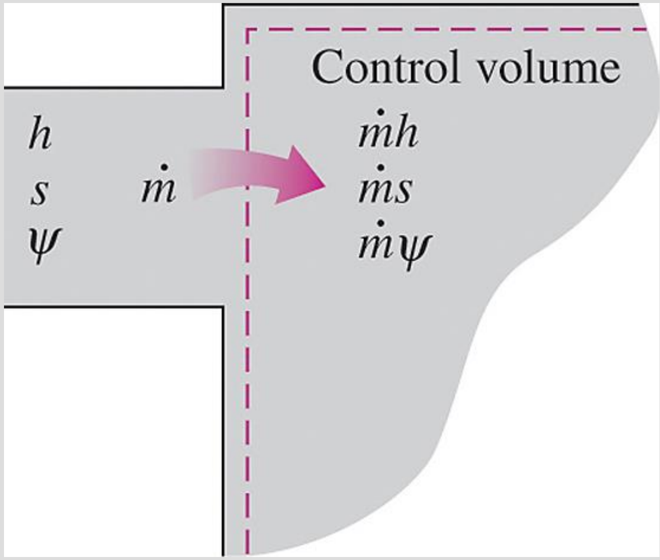
Exergy Transfer by Mass, *m*

$$X_{mass} = m\psi$$

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$\dot{X}_{mass} = \int_{A_c} \psi\rho V_n \, dA_c$$

$$X_{mass} = \int \psi \, \delta m = \int_{\Delta t} \dot{X}_{mass} \, dt$$



Mass contains energy, entropy, and exergy, and thus mass flow into or out of a system is accompanied by energy, entropy, and exergy transfer.

Summary

- Exergy: Work potential of energy
    - ✓ Exergy (work potential) associated with kinetic and potential energy
- Reversible work and irreversibility
- Second-law efficiency
- Exergy change of a system
    - ✓ Exergy of a fixed mass: Nonflow (or closed system) exergy
    - ✓ Exergy of a flow stream: Flow (or stream) exergy
- Exergy transfer by heat, work, and mass
- The decrease of exergy principle and exergy destruction
- Exergy balance: Closed systems
- Exergy balance: Control volumes
    - ✓ Exergy balance for steady-flow systems
    - ✓ Reversible work
    - ✓ Second-law efficiency of steady-flow devices