ENERGY
AND
THE FIRST LAW OF THERMODYNAMICS

MEG 212 Week 4 Lecture

Lecture Learning Outcomes

At the end of this lecture, you will be able to,

- Recall the evaluation of expansion work in a closed system
- State the first law of thermodynamics
- Apply the first law of thermodynamics to obtain net work done or net heat transfer in processes
- Apply the energy balance rate to steady and transient state operations

Worked Example 2: Evaluation of Work in a Process

- **Evaluate the work in kJ, for a two step process consisting of an expansion with $n = 1.0$ from initial pressure is 3 bar and the initial volume is 0.1 m³ to final volume is 0.15 m³ followed by and expansion with $n = 0$ from initial volume is 0.15 m³ to final volume is 0.2 m³**

$$pV^n = constant$$

Solution 1st Work Process 1 to 2

$$p_1 {V_1}^1 = p_2 {V_2}^1 = c; \;\; p_2 = p_1 \left(\frac{V_1}{V_2}\right)^1 = 2\, bar$$

We can now determine the work for the process

$$W = \int_{V_1}^{V_2} p\, dV = \int_{V_1}^{V_2} \frac{c}{V^n}\, dV = \int_{V_1}^{V_2} \frac{c}{V^1}\, dV$$

$$= c \ln V \Big|_{V1}^{V2} = c \ln \frac{V_2}{V_1} = p_1 V_1 \ln \frac{V_2}{V_1} = +12.16\, kJ$$

Worked Example 2: Evaluation of Work in a Process

- **Evaluate the work in kJ, for a two step process consisting of an expansion with $n = 1.0$ from initial pressure is 3 bar and the initial volume is 0.1 m³ to final volume is 0.15 m³ followed by and expansion with $n = 0$ from initial volume is 0.15 m³ to final volume is 0.2 m³**

$$pV^n = constant$$

Solution 2nd Work Process 2 to 3

$$p_2{V_2}^0 = p_3{V_3}^0 = c;\ \ p_2 = p_3 = 2\ bar$$

We can now determine the work for the process

$$W = \int_{V_2}^{V_3} p\ dV = p\int_{V_2}^{V_3} dV = p(V_3 - V_2)$$
$$= +10\ kJ$$

Total work as a result of the two processes is

$$+\ 22.16\ kJ$$

Change in Total Energy of a System

The change in the total energy of a system in engineering thermodynamics is considered to be made up of three macroscopic contributions

- ✓ Change in kinetic energy
- ✓ Change in gravitational potential energy
- ✓ All other energy changes lumped together in internal energy

Mathematically, the change in total energy of a system is expressed as,

$$E_2 - E_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1)$$

Which can also be written as

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Energy Transfer by Heat

Closed systems can also interact with their surroundings in a way that cannot be categorized as work.

For example, when gas in a rigid container interacts with a hot plate, the energy of the gas is increased even though no work is done.

This type of interaction is called energy transfer by heat

Q is used to denote an amount of energy transferred across the boundary of a system in a heat interaction with the surroundings

Energy Transfer by Heat: Sign Convention

The sign convention for heat transfer is just the reverse of the one adopted for work, where a positive value for work signifies an energy transfer from the system to the surroundings

When heat is transferred into a system, it is taken to be positive while the reverse is negative

$Q > 0$: Heat transfer to the system

$Q < 0$: Heat transfer from the system

Heat Transfer: Sign Convention and Notation

The value of Q depends on the details of interactions taking place between the system and surroundings during a process not just on the end states. Therefore, heat is not a property of the system or surroundings

$$\int_1^2 \delta Q = Q$$

The amount of energy transfer by heat is given by the integral above, where the limits of the integral means 'from state 1 to 2' and does not refer to the values of heat at the state (value of heat at each state has no meaning)

Heat Transfer: Sign Convention and Notation

The net rate of heat transfer is denoted by $\dot{Q}$. The energy transfer by heat during a period of time can be found by integrating from time t_1 to t_2

If a system undergoes a process involving no heat transfer with its surroundings, that process is called an adiabatic process

Rate of energy transfer by heat

$$Q = \int_{t_1}^{t_2} \dot{Q} dt$$

Modes of Heat transfer will be discussed in details in a Heat Transfer Course

Energy Balance for Closed Systems

- **A fundamental aspect of the energy concept is that energy is conserved**
- **This is called the first law of thermodynamics**
- **The first law of thermodynamics states that,**
- $$\begin{bmatrix} change\ in \\ amount\ of\ energy \\ contained \\ within\ a\ system \\ during\ some\ time\ interval \end{bmatrix} = \begin{bmatrix} net\ amount\ of\ energy \\ transferred\ in\ across \\ the \\ system\ boundary\ by \\ heat\ transfer\ during \\ the\ time\ interval \end{bmatrix} - \begin{bmatrix} net\ amount\ of \\ energy\ transferred \\ out\ across\ the \\ system\ boundary \\ by\ work\ during \\ the\ time\ interval \end{bmatrix}$$

Energy Balance for Closed Systems

- **The statement of the first law of thermodynamics is an accounting balance for energy**

- **It requires that in any process of a closed system, the energy of the system increases or decreases by an amount equal to the net amount of energy transferred across its boundary**

- **The statement of the 1st law can be written mathematically as,**

$$E_2 - E_1 = Q - W$$

$$\Delta KE + \Delta PE + \Delta U = Q - W$$

Energy Balance for Closed Systems

- **In differential form, the energy balance can be written as,**

$$dE = \delta Q - \delta W$$

- **The instantaneous time rate form is**

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

- **Which can be written alternatively as,**

$$\frac{dKE}{dt} + \frac{dPE}{dt} + \frac{dU}{dt} = \dot{Q} - \dot{W}$$

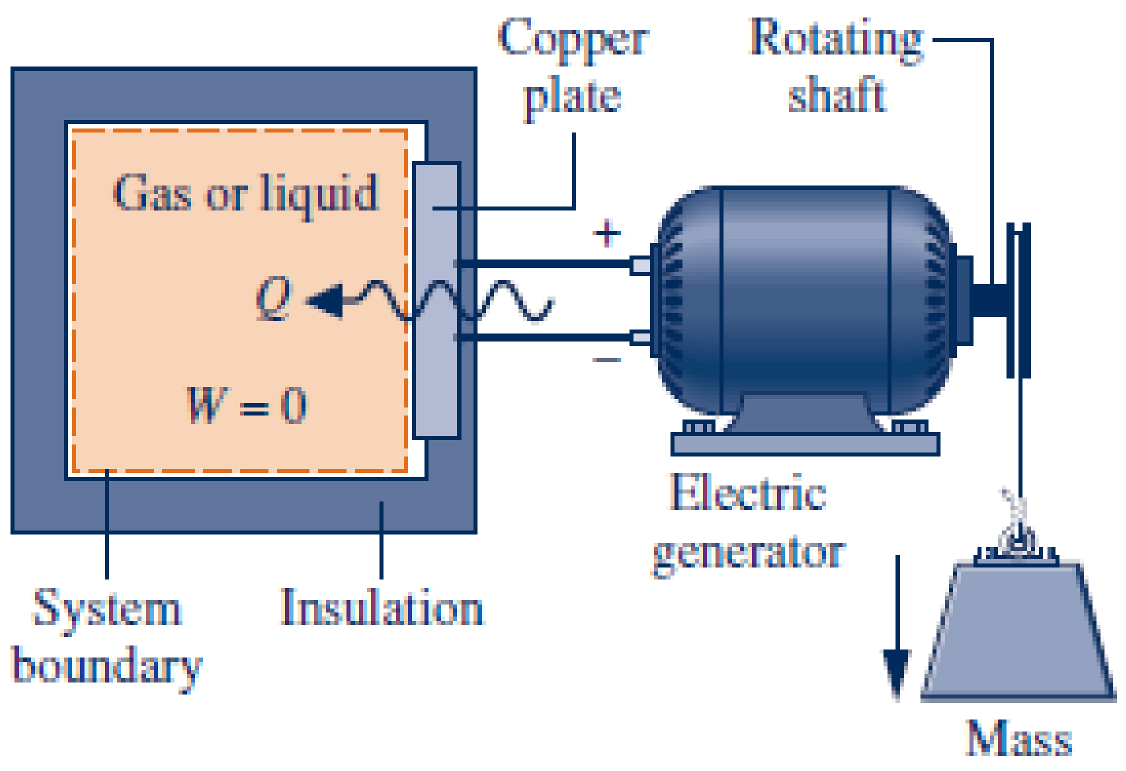
Energy Balance for Closed Systems

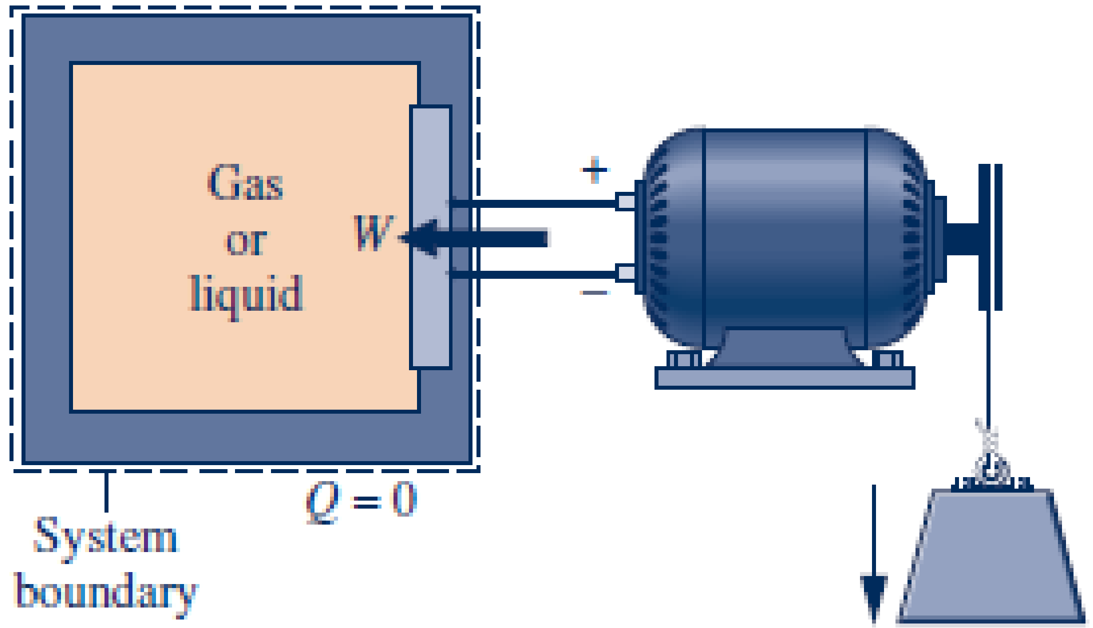
- **Important things to note about energy balance**

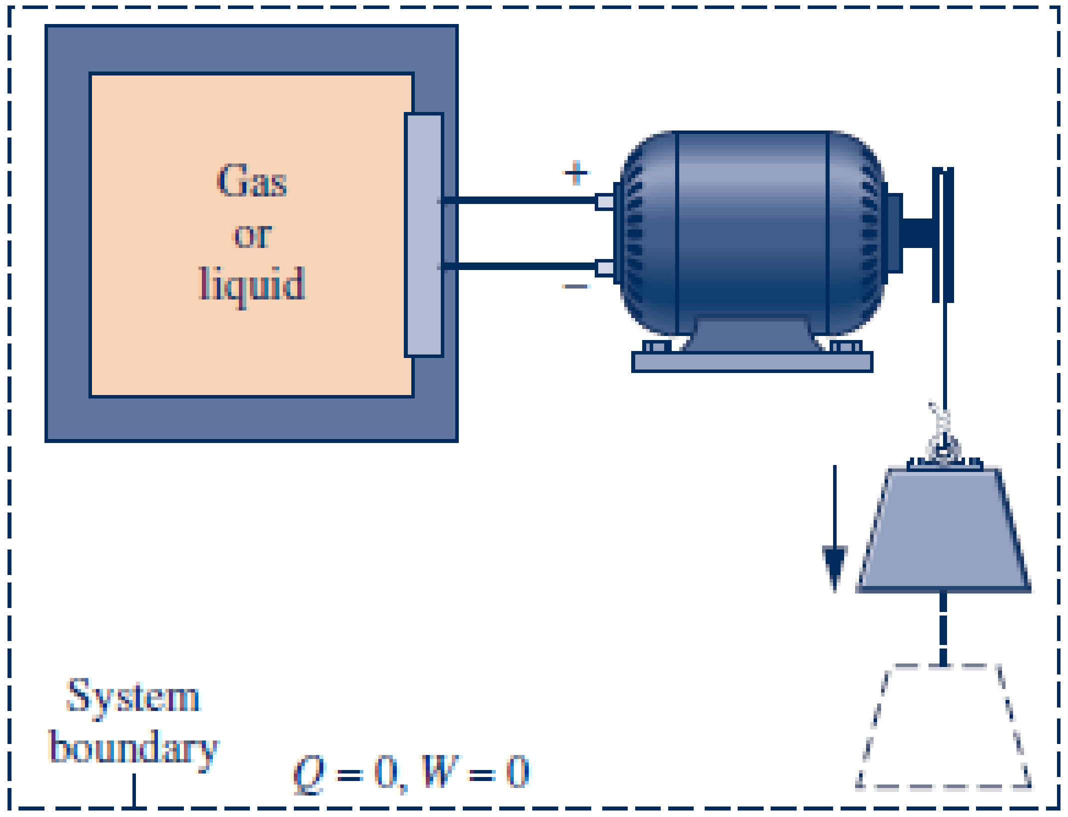
✓ **Be careful about signs and units**

✓ **Recognize the location of the system boundary**

- **The figures below show three alternative systems than show how recognize the system boundary**





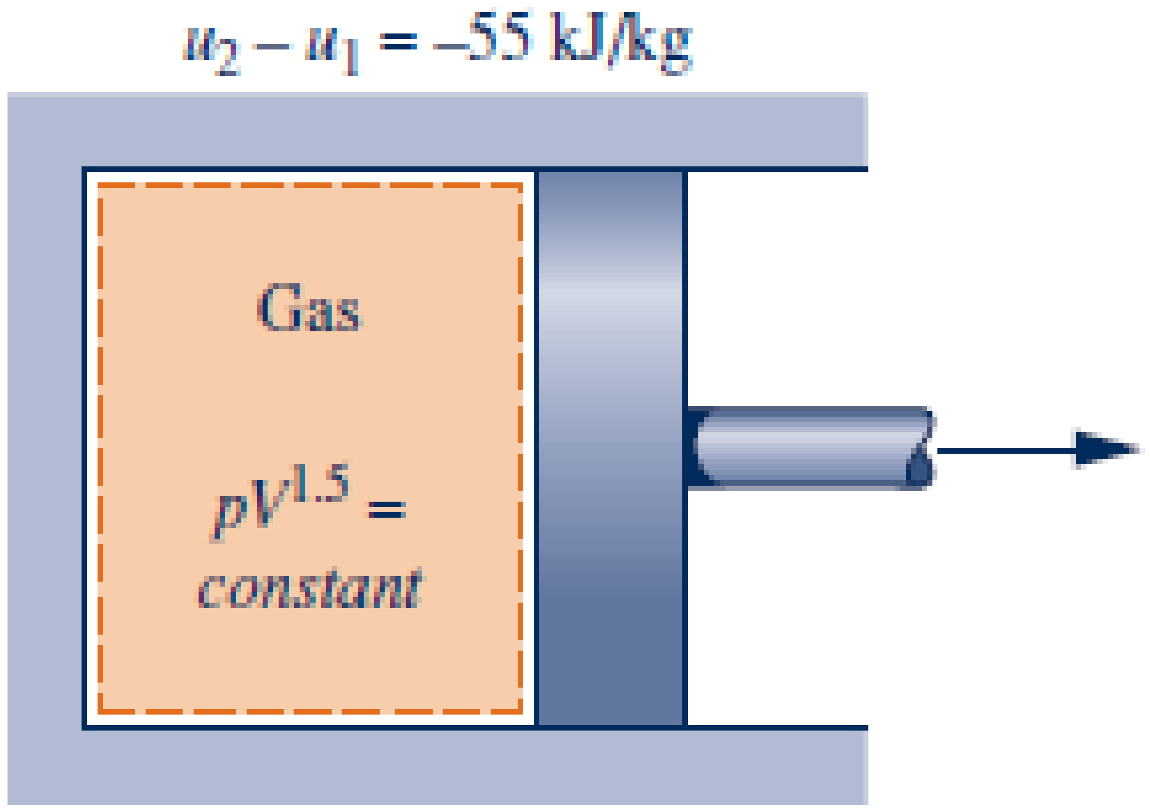


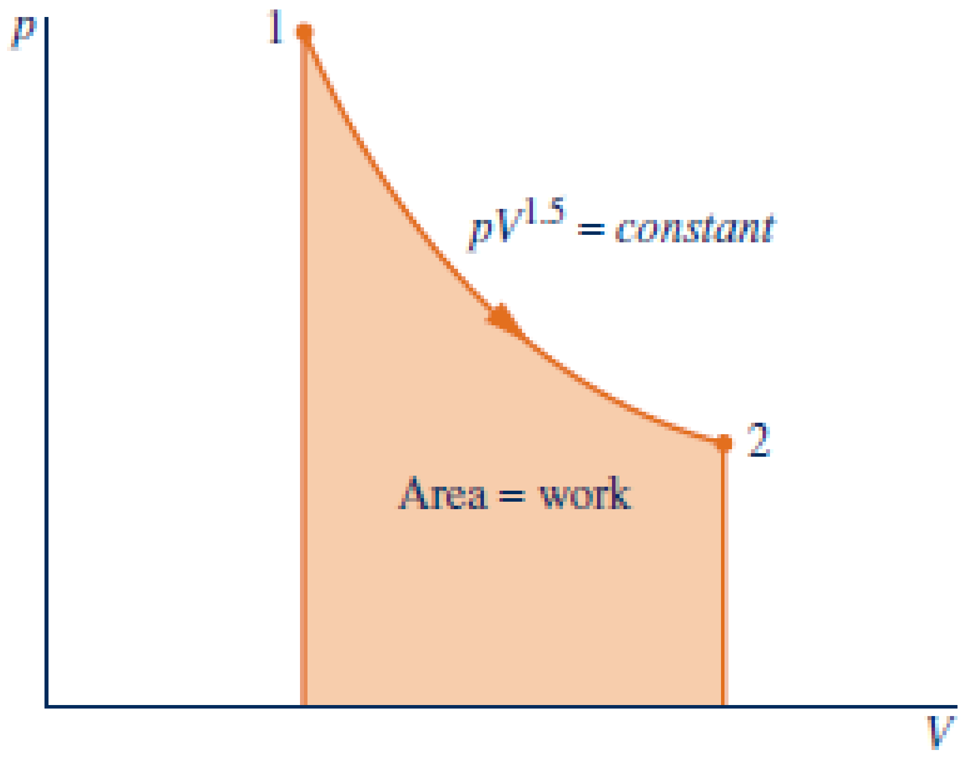
Energy Balance for Closed Systems: Example

- **Cooling a gas in a piston-cylinder assembly**

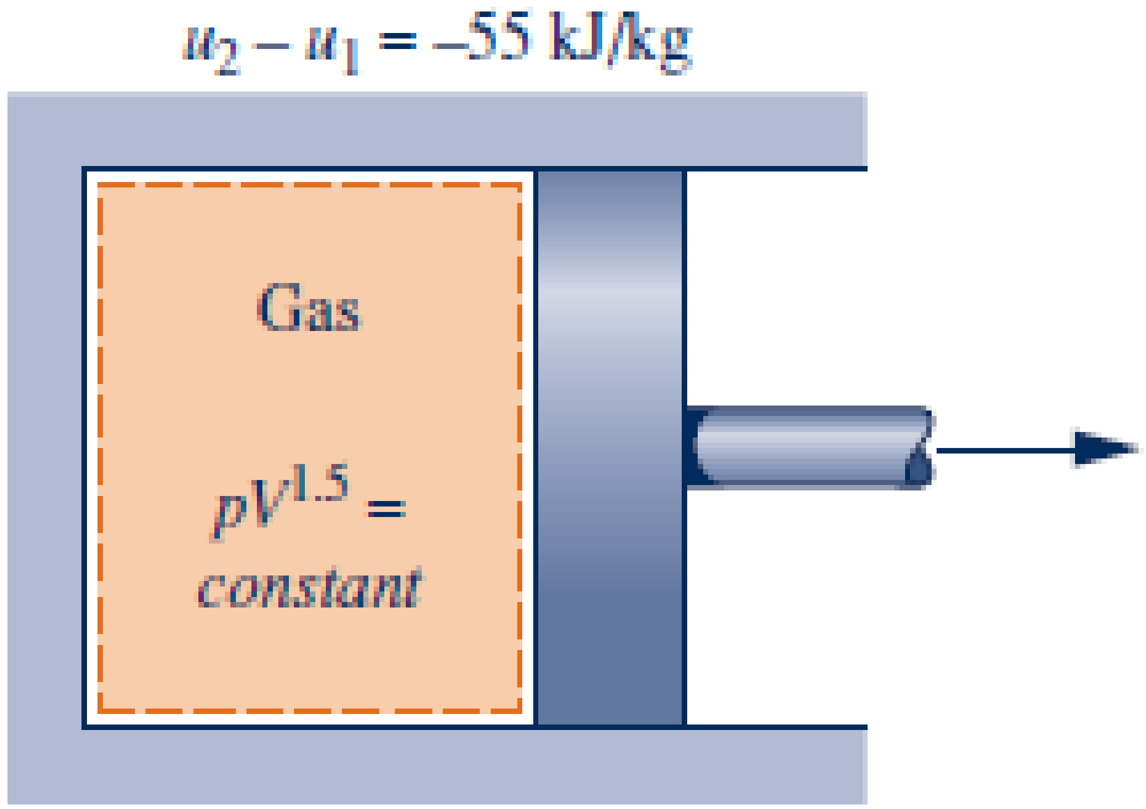
Four-tenths kilogram of a certain gas is contained within a piston-cylinder assembly. The gas undergoes a process for which the pressure-volume relationship is $pV^{1.5} = c$.

The initial pressure is 3 bar, the initial volume is $0.1m^3$ and the final volume is $0.2m^3$. The change in specific internal energy of the gas in the process is $u_2 - u_1 = -55$ kJ/kg. There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process





Energy Balance for Closed Systems: Example



- **Engineering Model**

✓ **The gas is a closed system**
✓ **The process is described by $pV^{1.5} = c$**
✓ **There is no change in KE and PE of the system**

$$\Delta KE + \Delta PE + \Delta U = Q - W$$

$$\Delta U = Q - W$$

$$\Delta U = m(u_2 - u_1) = -55kJ/kg$$

$$W = +17.6\ kJ$$

(Solution for W can be found in the example solved during the last lecture)

$$Q = \Delta U + W$$

$$Q = m(u_2 - u_1) + W = 0.4(-55) + 17.6$$

$$Q = -4.4\ kJ$$

There is heat transfer out of the system to the surroundings

Energy Balance for Closed Systems: Example

Class Exercise 1

If the gas undergoes a process for which $pV = c$ and $\Delta u = 0$, determine the heat transfer in kJ keeping the initial pressure and volume fixed.

Answer: $+\,20.79\ kJ$

Class Exercise 2

A closed system of mass 10 kg undergoes a process during which there is energy transfer by work from the system of 0.147 kJ per kg, an elevation decrease of 50m and an increase in velocity from 15 m/s to 30 m/s. The specific internal energy decreases by 5 kJ/kg and the acceleration due to gravity is 9.7m/s^2. Determine the heat transfer for the process in kJ.

Energy Rate Balance for Steady State Operation

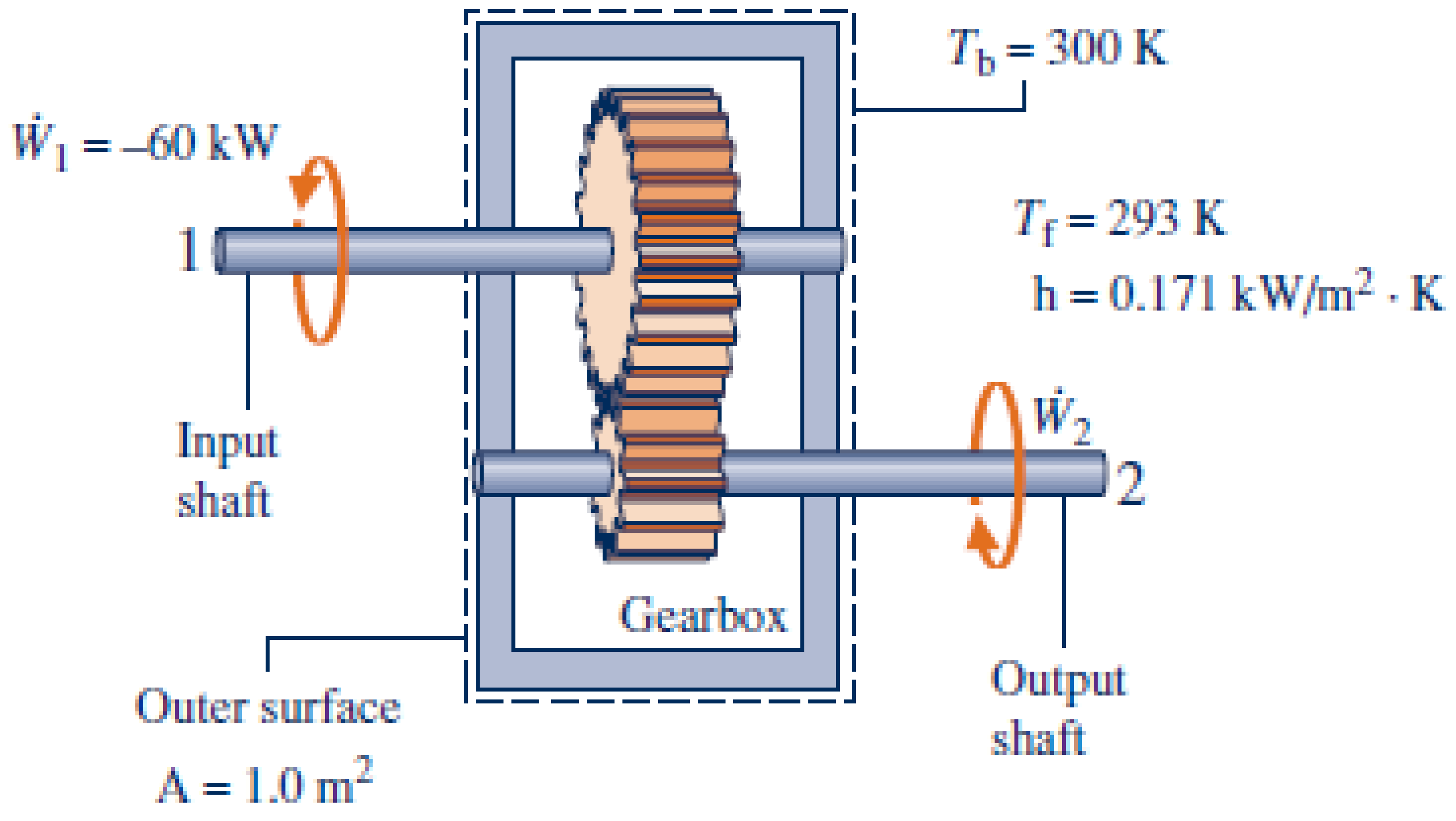
A system is at steady state if none of its properties change with time.

In real applications, when property variations with time are small enough to ignore, the devices are assumed to be at steady state

Example: Energy Transfer Rates of a Gearbox at Steady State

During steady state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox system, the rate of energy convection heat transfer is given by $\dot{Q} = hA(T_b - T_f)$ where $h = 0.171$ kW/m².K is the heat transfer coefficient , $A = 1.0m^2$ is the outer surface of the gearbox, $T_b = 300\ K\ (27°\text{C})$ is the temperature of the outer surface and $T_f = 293\ K\ (20°\text{C})$ is the temperature of the surrounding air away from the immediate vicinity of the gearbox. For the gearbox, evaluate the heat transfer rate and power delivered through the output shaft in kW.

Energy Rate Balance for Steady State Operation



- **Engineering Model**

✓ **The gearbox is a closed system at steady state**

✓ **Convection is the dominant heat transfer**

✓ **Energy by heat is transferred out of the system**

Known: Expression for heat transfer rate and power input are given

Find: Heat transfer rate and power output in kW

$$\dot{Q} = hA(T_b - T_f)$$
$$= 0.171 \times 1 \times (300 - 293) = 1.2\ kW$$

Because heat is transferred out of the system $\dot{Q} = -1.2\ kW$

$$\dot{W} = -\dot{W}_1 + \dot{W}_2$$
$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

For steady state, the energy rate balance reduces to

$$0 = \dot{Q} - \dot{W}, \qquad \dot{Q} = \dot{W}$$

Therefore,

$$-1.2 = -60 + \dot{W}_2, \qquad \dot{W}_2 = +58.8\ kW$$

Energy Rate Balance for Transient State Operation

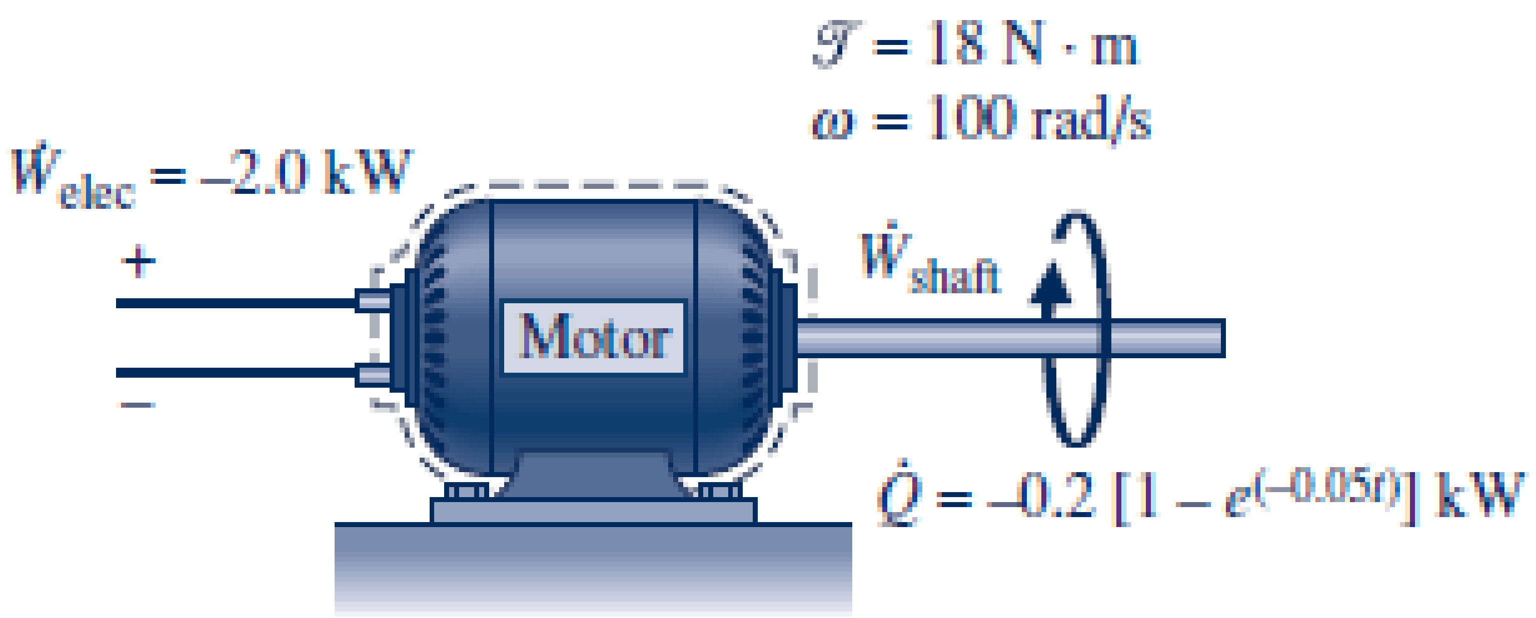
Many devices undergo periods of transient operation where the state changes with time.

This is observed during startup and shutdown periods

Example: Transient Operation of a Motor

The rate of heat transfer between a certain electric motor and its surroundings varies with time as $\dot{Q} = -0.2\left[1 - e^{(-0.05t)}\right]$ where t is in seconds and $\dot{Q}$ is in kW. The shaft of the motor rotates at constant speed $\omega = 100\, rad/s$ (about 955 revolutions per minute) and applies a constant torque, $\mathfrak{I} = 18\, N.m$ to an external load. The motor draws a constant electric power input of 2.0 kW. For the motor use a spreadsheet to tabulate $\dot{Q}$ and $\dot{W}$ in kW and the change in energy ΔE in kJ as functions of time from $t = 0\, s$ to $t = 120\, s$

Energy Rate Balance for Steady State Operation



- **Engineering Model**

✓ **The figure shows details of the model**

Known: time-varying rate of heat transfer between motor and its surroundings is given

Find: Changes in the rate of heat transfer, power and energy as time changes

$$\frac{dE}{dt} = \dot{Q} - \dot{W}, \qquad \dot{W}_{shaft} = \Im\omega = +1.8\ kW$$

$$\dot{W} = -\dot{W}_{elec} + \dot{W}_{shaft} = -2 + 1.8 = -0.2\ kW$$

$$\frac{dE}{dt} = -0.2\left[1 - e^{(-0.05t)}\right] - (-0.2) = 0.2e^{-0.05t}$$

To obtain the change in energy we perform an integration

$$\Delta E = \int_0^t 0.2e^{-0.05t}\,dt = 4\left[1 - e^{(-0.05t)}\right]$$

Class exercise: Table of values for Changes in the rate of heat transfer, power and energy as time changes

SUMMARY

1. Review of Evaluation of work in a process
2. Change in total energy of a system
3. Energy transfer by heat
Sign Convention
&
Notation
4. Energy balance for closed systems – 1st law of thermodynamics
5. Worked Examples
Energy Balance for closed systems
6. Worked Examples
Energy rate balance –
Steady & Transient states

Next Lecture

- **Energy balance for power, refrigeration and heat pump cycles**
- **Revision for First Quiz**

- **ANSYS Hands-On Tutorial 1 – Friday December 1, 2023**
- **First Quiz, Friday December 8, 2023**