University of Anbar

Engineering Thermodynamics
CHE 215

Lecture # 05

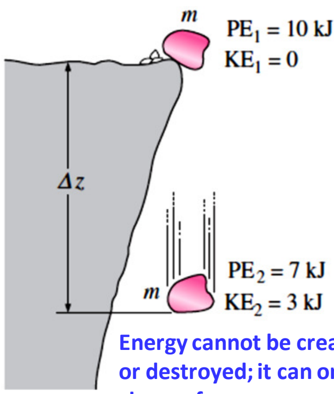
Energy, Energy Transfer, and General Energy Analysis

Objective of Lecture Note

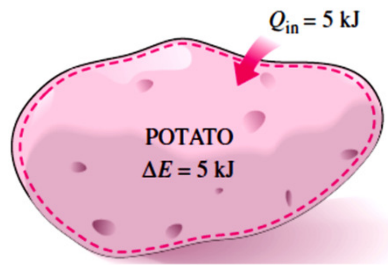
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.

The First Law of Thermodynamics

- The *first law of thermodynamics* (*the conservation of energy principle*) **provides a sound basis for studying the relationships among the various forms of energy and energy interactions.**
- **The first law states that** *energy can be neither created nor destroyed during a process; it can only change forms*.
- The *First Law:* **For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.**



Energy cannot be created or destroyed; it can only change forms.



The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

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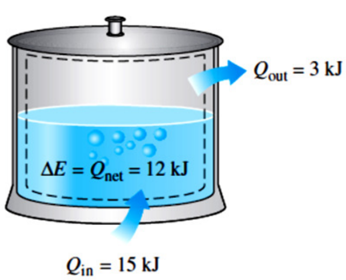
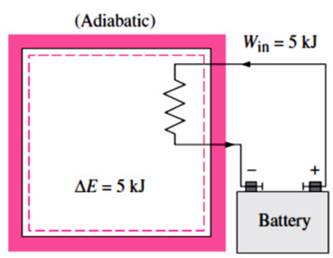
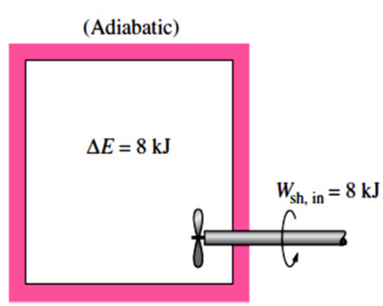
The First Law of Thermodynamics



In the absence of any work interactions, the energy change of a system is equal to the NET HEAT TRANSFER.



The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.



The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

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The First Law of Thermodynamics

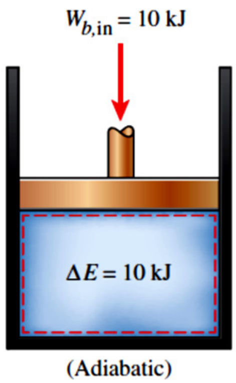

FIGURE 2–44
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

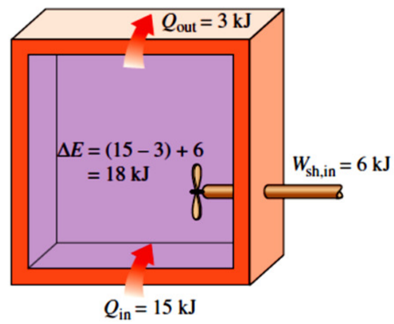

FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

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Energy Balance

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

or

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

This relation is often referred to as the *energy balance* and is applicable to any kind of system undergoing any kind of process. The successful use of this relation to solve engineering problems depends on understanding the various forms of energy and recognizing the forms of energy transfer.

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Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

or

$$\Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta \text{KE} = \tfrac{1}{2} m(V_2^2 - V_1^2)$$

$$\Delta \text{PE} = mg(z_2 - z_1)$$

Energy is a property, and the value of a property does not change unless the state of the system changes. Therefore, the energy change of a system is zero if the state of the system does not change during the process.

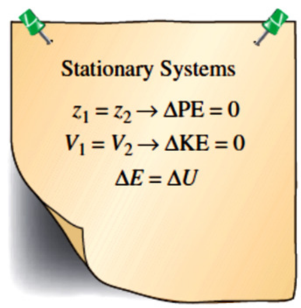


FIGURE 2–46
For stationary systems, $\Delta \text{KE} = \Delta \text{PE} = 0$; thus $\Delta E = \Delta U$.

Mechanisms of Energy Transfer, E_{in} and E_{out}

$$E_{\text{in}} - E_{\text{out}} = (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass,in}} - E_{\text{mass,out}}) = \Delta E_{\text{system}}$$

Heat transfer
Work transfer
Mass flow

A closed mass involves only *heat transfer* and *work*.

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

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad (\text{kW})$$

$$Q = \dot{Q}\,\Delta t \quad (\text{kJ})$$

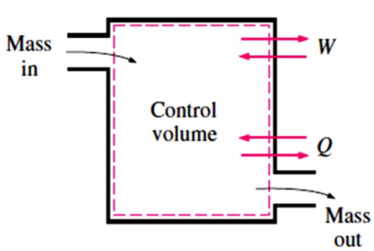
$$W = \dot{W}\,\Delta t$$

$$\Delta E = (dE/dt)\,\Delta t$$

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}} \quad (\text{kJ/kg})$$

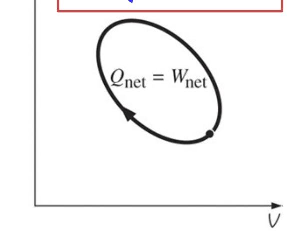
$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \qquad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}}$$

$$W_{\text{net,out}} = Q_{\text{net,in}} \quad \text{or} \quad \dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}} \quad (\text{for a cycle})$$



The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

For a cycle $\Delta E = 0$, thus $Q = W$.



EXAMPLE 2–10 Cooling of a Hot Fluid in a Tank

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

Solution A fluid in a rigid tank looses heat while being stirred. The final internal energy of the fluid is to be determined.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$. Therefore, $\Delta E = \Delta U$ and internal energy is the only form of the system's energy that may change during this process. **2** Energy stored in the paddle wheel is negligible.

Analysis Take the contents of the tank as the *system* (Fig. 2–47). This is a *closed system* since no mass crosses the boundary during the process. We observe that the volume of a rigid tank is constant, and thus there is no moving boundary work. Also, heat is lost from the system and shaft work is done on the system. Applying the energy balance on the system gives

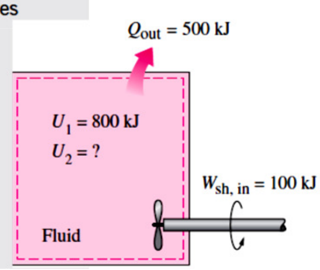
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$

$$U_2 = \mathbf{400\ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.



Example 2

A vertical piston–cylinder device contains water and is being heated on top of a range. During the process, $65\ Btu$ of heat is transferred to the water, and heat losses from the side walls amount to $8\ Btu$. The piston rises as a result of evaporation, and $5\ Btu$ of work is done by the vapor. Determine the change in the energy of the water for this process.

Analysis: We take the water in the cylinder as the system. This is a closed system since no mass enters or leaves. Applying the energy balance on this system gives

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

$$Q_{in} - W_{out} - Q_{out} = \Delta U = U_2 - U_1$$

$$65 \text{ Btu} - 5 \text{ Btu} - 8 \text{ Btu} = \Delta U$$

$$\Delta U = U_2 - U_1 = \mathbf{52\ \ Btu}$$

Therefore, the energy content of the system increases by 52 Btu during this process.

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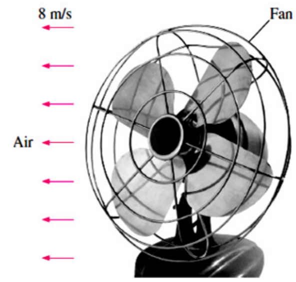
EXAMPLE 2–11 Acceleration of Air by a Fan

A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 1.0 kg/s at a discharge velocity of 8 m/s (Fig. 2–50). Determine if this claim is reasonable.



SOLUTION A fan is claimed to increase the velocity of air to a specified value while consuming electric power at a specified rate. The validity of this claim is to be investigated.

Assumptions The ventilating room is relatively calm, and air velocity in it is negligible.

Analysis First, let's examine the energy conversions involved: The motor of the fan converts part of the electrical power it consumes to mechanical (shaft) power, which is used to rotate the fan blades in air. The blades are shaped such that they impart a large fraction of the mechanical power of the shaft to air by mobilizing it. In the limiting ideal case of no losses (no conversion of electrical and mechanical energy to thermal energy) in steady operation, the electric power input will be equal to the rate of increase of the kinetic energy of air. Therefore, for a control volume that encloses the fan-motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0\,(steady)}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{elect,\,in} = \dot{m}_{air}\,ke_{out} = \dot{m}_{air}\frac{V_{out}^2}{2}$$

Solving for V_{out} and substituting gives the maximum air outlet velocity to be

$$V_{out} = \sqrt{\frac{2\dot{W}_{elect,in}}{\dot{m}_{air}}} = \sqrt{\frac{2(20\text{ J/s})}{1.0\text{ kg/s}}\left(\frac{1\text{ m}^2/\text{s}^2}{1\text{ J/kg}}\right)} = 6.3\text{ m/s}$$

which is less than 8 m/s. Therefore, the claim is **false**.

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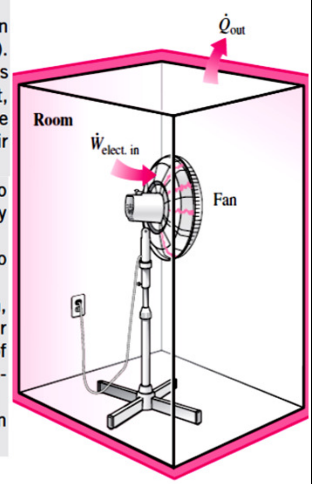
EXAMPLE 2–12 Heating Effect of a Fan

A room is initially at the outdoor temperature of 25°C. Now a large fan that consumes 200 W of electricity when running is turned on (Fig. 2–49). The heat transfer rate between the room and the outdoor air is given as $\dot{Q} = UA(T_i - T_o)$ where $U = 6$ W/m² · °C is the overall heat transfer coefficient, $A = 30$ m² is the exposed surface area of the room, and T_i and T_o are the indoor and outdoor air temperatures, respectively. Determine the indoor air temperature when steady operating conditions are established.



Solution A large fan is turned on and kept on in a room that looses heat to the outdoors. The indoor air temperature is to be determined when steady operation is reached.

Assumptions **1** Heat transfer through the floor is negligible. **2** There are no other energy interactions involved.

Analysis The electricity consumed by the fan is energy input for the room, and thus the room gains energy at a rate of 200 W. As a result, the room air temperature tends to rise. But as the room air temperature rises, the rate of heat loss from the room increases until the rate of heat loss equals the electric power consumption. At that point, the temperature of the room air, and thus the energy content of the room, remains constant, and the conservation of energy for the room becomes

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0\,(steady)}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{elect,in} = \dot{Q}_{out} = UA(T_i - T_o)$$

Substituting,

$$200\text{ W} = (6\text{ W/m}^2\cdot{}^\circ\text{C})(30\text{ m}^2)(T_i - 25^\circ\text{C})$$

It gives

$$T_i = \mathbf{26.1^\circ C}$$

Therefore, the room air temperature will remain constant after it reaches 26.1°C.

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Example 5

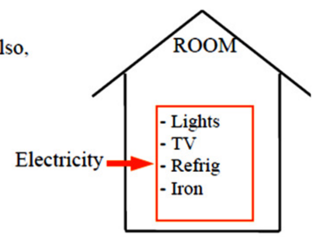
Consider a room that is initially at the outdoor temperature of $20°C$. The room contains a $100W$ lightbulb, a $110W$ TV set, a $200W$ refrigerator, and a $1000W$ iron. Assuming no heat transfer through the walls, determine the rate of increase of the energy content of the room when all of these electric devices are on.

Analysis: Taking the room as the system, the rate form of the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} \rightarrow dE_{room}/dt = \dot{E}_{in}$$

since no energy is leaving the room in any form, and thus $\dot{E}_{out} = 0$. Also,

$$\dot{E}_{in} = \dot{E}_{lights} + \dot{E}_{TV} + \dot{E}_{refrig} + \dot{E}_{iron}$$
$$= 100 + 110 + 200 + 1000 \text{ W}$$
$$= 1410 \text{ W}$$



Substituting, the rate of increase in the energy content of the room becomes

$$dE_{room}/dt = \dot{E}_{in} = \mathbf{1410\ W}$$

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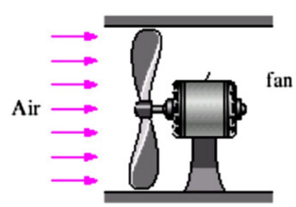
Example 7

A fan is to accelerate quiescent air to a velocity of 10 m/s at a rate of $4\ m^3/s$. Determine the minimum power that must be supplied to the fan. Take the density of air to be $1.18\ kg/m^3$.

Analysis: A fan transmits the mechanical energy of the shaft (shaft power) to mechanical energy of air (kinetic energy). For a control volume that encloses the fan, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0\ \text{(steady)}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{sh,\,in} = \dot{m}_{air}\,\text{ke}_{out} = \dot{m}_{air}\frac{V_{out}^2}{2}$$



where

$$\dot{m}_{air} = \rho\dot{V} = (1.18 \text{ kg/m}^3)(4 \text{ m}^3/\text{s}) = 4.72 \text{ kg/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{sh,\,in} = \dot{m}_{air}\frac{V_{out}^2}{2} = (4.72 \text{ kg/s})\frac{(10 \text{ m/s})^2}{2}\left(\frac{1 \text{ J/kg}}{1 \text{ m}^2/\text{s}^2}\right) = 236 \text{ J/s} = \mathbf{236\ W}$$

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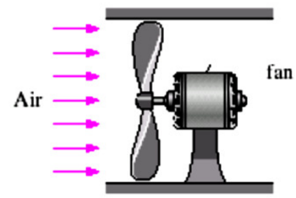
Example 8

Consider a fan located in a 3 ft x 3 ft square duct. Velocities at various points at the outlet are measured, and the average flow velocity is determined to be 22 ft/s. Taking the air density to $0.075\ lbm/ft^3$, estimate the minimum electric power consumption of the fan motor.

Analysis: A fan motor converts electrical energy to mechanical shaft energy, and the fan transmits the mechanical energy of the shaft (shaft power) to mechanical energy of air (kinetic energy). For a control volume that encloses the fan-motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0\ (steady)}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{elect,in} = \dot{m}_{air}\,ke_{out} = \dot{m}_{air}\frac{V_{out}^2}{2}$$



where

$$\dot{m}_{air} = \rho VA = (0.075\ \text{lbm/ft}^3)(3\times 3\ \text{ft}^2)(22\ \text{ft/s}) = 14.85\ \text{lbm/s}$$

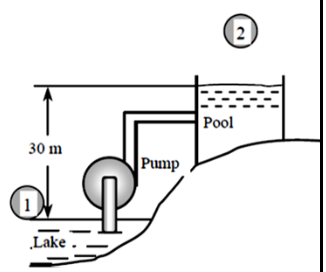
Substituting, the minimum power input required is determined to be

$$\dot{W}_{in} = \dot{m}_{air}\frac{V_{out}^2}{2} = (14.85\ \text{lbm/s})\frac{(22\ \text{ft/s})^2}{2}\left(\frac{1\ \text{Btu/lbm}}{25{,}037\ \text{ft}^2/\text{s}^2}\right) = 0.1435\ \text{Btu/s} = \mathbf{151\ W}$$

since 1 Btu = 1.055 kJ and 1 kJ/s = 1000 W.

Example 9

A water pump that consumes $2\ kW$ of electric power when operating is claimed to take in water from a lake and pump it to a pool whose free surface is $30\ m$ above the free surface of the lake at a rate of $50\ L/s$. Determine if this claim is reasonable.



Analysis: For a control volume that encloses the pump motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0\ (steady)}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}pe_1 = \dot{m}pe_2 \quad \rightarrow \quad \dot{W}_{in} = \dot{m}\Delta pe = \dot{m}g(z_2 - z_1)$$

since the changes in kinetic and flow energies of water are negligible. Also,

$$\dot{m} = \rho\dot{V} = (1\ \text{kg/L})(50\ \text{L/s}) = 50\ \text{kg/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{in} = \dot{m}g(z_2 - z_1) = (50\ \text{kg/s})(9.81\ \text{m/s}^2)(30\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 14.7\ \text{kJ/s} = \mathbf{14.7\ kW}$$

which is much greater than 2 kW. Therefore, the claim is false

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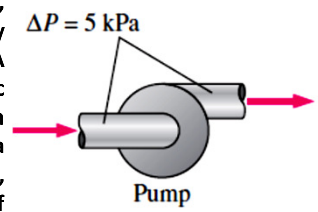
Example 10

The driving force for fluid flow is the pressure difference, and a pump operates by raising the pressure of a fluid (by converting the mechanical shaft work to flow energy). A gasoline pump is measured to consume 5.2 kW of electric power when operating. If the pressure differential between the outlet and inlet of the pump is measured to be 5 kPa and the changes in velocity and elevation are negligible, determine the maximum possible volume flow rate of gasoline.



Analysis: For a control volume that encloses the pump-motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}(P\boldsymbol{v})_1 = \dot{m}(P\boldsymbol{v})_2 \rightarrow \dot{W}_{in} = \dot{m}(P_2 - P_1)\boldsymbol{v} = \dot{V}\,\Delta P$$

since $\dot{m} = \dot{V}/\boldsymbol{v}$ and the changes in kinetic and potential energies of gasoline are negligible. Solving for volume flow rate and substituting, the maximum flow rate is determined to be

$$\dot{V}_{max} = \frac{\dot{W}_{in}}{\Delta P} = \frac{5.2 \text{ kJ/s}}{5 \text{ kPa}}\left(\frac{1 \text{ kPa}\cdot\text{m}^3}{1 \text{ kJ}}\right) = \mathbf{1.04\ m^3/s}$$

Example 11

The 60-W fan of a central heating system is to circulate air through the ducts. The analysis of the flow shows that the fan needs to raise the pressure of air by 50 Pa to maintain flow. The fan is located in a horizontal flow section whose diameter is 30 cm at both the inlet and the outlet. Determine the highest possible average flow velocity in the duct.

Analysis: For a control volume that encloses the fan unit, the energy balance can be written as

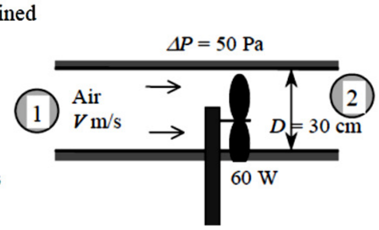
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \rightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}(Pv)_1 = \dot{m}(Pv)_2 \rightarrow \dot{W}_{in} = \dot{m}(P_2 - P_1)v = \dot{V}\,\Delta P$$

since $\dot{m} = \dot{V}/\boldsymbol{v}$ and the changes in kinetic and potential energies of gasoline are negligible. Solving for volume flow rate and substituting, the maximum flow rate and velocity are determined to be

$$\dot{V}_{max} = \frac{\dot{W}_{in}}{\Delta P} = \frac{60 \text{ J/s}}{50 \text{ Pa}}\left(\frac{1 \text{ Pa}\cdot\text{m}^3}{1 \text{ J}}\right) = 1.2 \text{ m}^3/\text{s}$$

$$V_{max} = \frac{\dot{V}_{max}}{A_c} = \frac{\dot{V}_{max}}{\pi D^2/4} = \frac{1.2 \text{ m}^3/\text{s}}{\pi(0.30 \text{ m})^2/4} = \mathbf{17.0\ m/s}$$

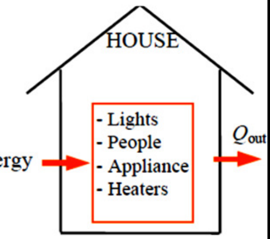


Example 12

At winter design conditions, a house is projected to lose heat at a rate of 60,000 Btu/h. The internal heat gain from people, lights, and appliances is estimated to be 6000 Btu/h. If this house is to be heated by electric resistance heaters, determine the required rated power of these heaters in kW to maintain the house at constant temperature.

Analysis: **Taking the house as the system, the energy balance can be written as**

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0\ \text{(steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$



where $\dot{E}_{out} = \dot{Q}_{out} = 60{,}000$ Btu/h and

$$\dot{E}_{in} = \dot{E}_{people} + \dot{E}_{lights} + \dot{E}_{appliance} + \dot{E}_{heater} = 6000 \text{ Btu/h} + \dot{E}_{heater}$$

Substituting, the required power rating of the heaters becomes

$$\dot{E}_{heater} = 60{,}000 - 6000 = 54{,}000 \text{ Btu/h}\left(\frac{1 \text{ kW}}{3412 \text{ Btu/h}}\right) = \mathbf{15.8\ kW}$$

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Example 13

An escalator in a shopping center is designed to move 30 people, 75 kg each, at a constant speed of 0.8 m/s at 45° slope. (a) Determine the minimum power input needed to drive this escalator. (b) What would your answer be if the escalator velocity were to be doubled?

Analysis: **At design conditions, the total mass moved by the escalator at any given time is**

Mass = (30 persons)(75 kg/person) = 2250 kg

The vertical component of escalator velocity is

$$V_{vert} = V \sin 45° = (0.8\ m/s)\sin 45°$$

Under stated assumptions, the power supplied is used to increase the potential energy of people. Taking the people on elevator as the closed system, the energy balance in the rate form can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{in} = dE_{sys}/dt \cong \frac{\Delta E_{sys}}{\Delta t}$$

$$\dot{W}_{in} = \frac{\Delta PE}{\Delta t} = \frac{mg\Delta z}{\Delta t} = mgV_{vert}$$

That is, under stated assumptions, the power input to the escalator must be equal to the rate of increase of the potential energy of people. Substituting, the required power input becomes

$$\dot{W}_{in} = mgV_{vert} = (2250 \text{ kg})(9.81 \text{ m/s}^2)(0.8 \text{ m/s})\sin 45°\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 12.5 \text{ kJ/s} = \mathbf{12.5\ kW}$$

When the escalator velocity is doubled to $V = 1.6$ m/s, the power needed to drive the escalator becomes

$$\dot{W}_{in} = mgV_{vert} = (2250 \text{ kg})(9.81 \text{ m/s}^2)(1.6 \text{ m/s})\sin 45°\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 25.0 \text{ kJ/s} = \mathbf{25.0\ kW}$$

Example 14

Consider a 1400-kg car cruising at constant speed of 70 km/h. Now the car starts to pass another car, by accelerating to 110 km/h in 5 s. Determine the additional power needed to achieve this acceleration. What would your answer be if the total mass of the car were only 700 kg?

Analysis: **We consider the entire car as the system, except that let's assume the power is supplied to the engine externally for simplicity (rather that internally by the combustion of a fuel and the associated energy conversion processes). The energy balance for the entire mass of the car can be written in the rate form as**

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0 \rightarrow \dot{E}_{in} = dE_{sys}/dt \cong \frac{\Delta E_{sys}}{\Delta t}$$

$$\dot{W}_{in} = \frac{\Delta KE}{\Delta t} = \frac{m(V_2^2 - V_1^2)/2}{\Delta t}$$

since we are considering the change in the energy content of the car due to a change in its kinetic energy (acceleration). Substituting, the required additional power input to achieve the indicated acceleration becomes

$$\dot{W}_{in} = m\frac{V_2^2 - V_1^2}{2\Delta t} = (1400\text{ kg})\frac{(110/3.6\text{ m/s})^2 - (70/3.6\text{ m/s})^2}{2(5\text{ s})}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 77.8\text{ kJ/s} = \mathbf{77.8\ kW}$$

since 1 m/s = 3.6 km/h. If the total mass of the car were 700 kg only, the power needed would be

$$\dot{W}_{in} = m\frac{V_2^2 - V_1^2}{2\Delta t} = (700\text{ kg})\frac{(110/3.6\text{ m/s})^2 - (70/3.6\text{ m/s})^2}{2(5\text{ s})}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{38.9\ kW}$$

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