University of Anbar

Engineering Thermodynamics
CHE 215

Lecture # 03

Energy, Energy Transfer, and General Energy Analysis

Objectives of Lecture Note

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.

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Introduction

- Energy is an important part of most aspects of daily life. The quality of life, and even its sustenance, depends on the availability of energy.
- Energy exists in numerous forms such as **thermal**, **mechanical**, **electric**, **chemical**, and **nuclear**. Even **mass** can be considered a form of energy.
- Energy can be transferred to or from a closed system (a fixed mass) in two distinct forms: ***heat*** and ***work***.
- For control volumes, energy can also be transferred by **mass flow**.
- An energy transfer to or from a closed system is ***heat*** if it is caused by a ***temperature difference***. Otherwise it is ***work***, and it is caused by a ***force*** acting through a distance.

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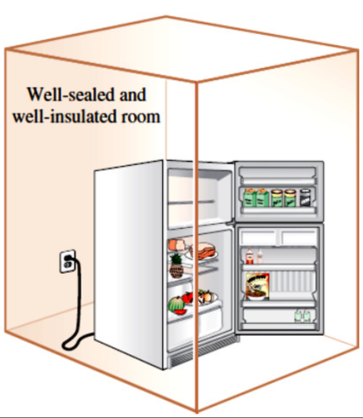
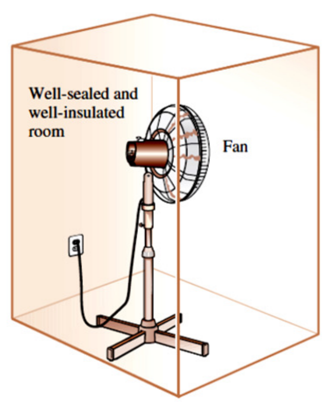
Introduction

- If we take the entire room—including the air and the refrigerator (or fan)—as the system, which is an adiabatic closed system since the room is well-sealed and well-insulated, the only energy interaction involved is the electrical energy crossing the system boundary and entering the room.
- As a result of the conversion of electric energy consumed by the device to heat, the room temperature will rise.



A refrigerator operating with its door open in a well-sealed and well-insulated room

A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room.



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Forms of Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, *E*** of a system.
- Thermodynamics deals only with the ***change*** of the total energy.

- **Macroscopic forms of energy:** Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **Kinetic energy, KE:** The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field.

Microscopic forms of energy: Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, *U*: The sum of all the microscopic forms of energy.

The macroscopic energy of an object changes with velocity and elevation.

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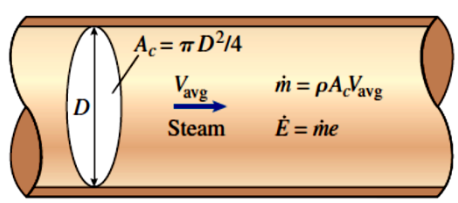
$$\mathrm{KE} = m\frac{V^2}{2} \quad (\mathrm{kJ})$$ Kinetic energy

$$\mathrm{ke} = \frac{V^2}{2} \quad (\mathrm{kJ/kg})$$ Kinetic energy per unit mass

$$\mathrm{PE} = mgz \quad (\mathrm{kJ})$$ Potential energy

$$\mathrm{pe} = gz \quad (\mathrm{kJ/kg})$$ Potential energy per unit mass



$$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz \quad (\mathrm{kJ})$$ Total energy of a system

$$e = \frac{E}{m} \quad (\mathrm{kJ/kg})$$ Total energy per unit mass

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \quad (\mathrm{kJ/kg})$$ Energy of a system per unit mass

closed system is assumed to be stationary unless stated otherwise. Thus $\Delta E = \Delta U$

$$\dot{m} = \rho\dot{V} = \rho A_c V_{\mathrm{avg}} \quad (\mathrm{kg/s})$$ Mass flow rate

$$\dot{E} = \dot{m}e \quad (\mathrm{kJ/s\ or\ kW})$$ Energy flow rate

The dot over a symbol is used to indicate ***time rate*** in this book.

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Mechanical Energy

- Many engineering systems are designed to transport a fluid from one location to another at a specified flow rate, velocity, and elevation difference, and the system may generate mechanical work in a turbine or it may consume mechanical work in a pump or fan during this process.
- These systems do not involve the conversion of nuclear, chemical, or thermal energy to mechanical energy. Also, they do not involve any heat transfer in any significant amount, and they operate essentially at constant temperature.
- Mechanical energy *is the form of energy that can be converted to mechanical work completely and directly by a mechanical device such as a turbine*. It differs from thermal energy in that thermal energy cannot be converted to work directly and completely. The forms of mechanical energy of a fluid stream are kinetic, potential, and flow energies.

Mechanical energy is a useful concept for flows that do not involve significant heat transfer or energy conversion, such as the flow of gasoline from an underground tank into a car.

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Mechanical Energy

$$e_{mech} = \frac{P}{\rho} + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

Mechanical energy of a flowing fluid per unit mass

Where $\frac{P}{\rho}$ is the *flow energy*, $\frac{V^2}{2}$ is the *kinetic energy*, and gz is the *potential energy* of the fluid, all per unit mass.

$$\dot{E}_{mech} = \dot{m}e_{mech} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{mech} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad \text{(kJ/kg)}$$

Rate of mechanical energy change of a fluid during incompressible flow ($\rho = constant$)

$$\Delta\dot{E}_{mech} = \dot{m}\Delta e_{mech} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \quad \text{(kW)}$$

Therefore, the mechanical energy of a fluid does not change during flow if its *pressure*, *density*, *velocity*, and *elevation* remain constant.

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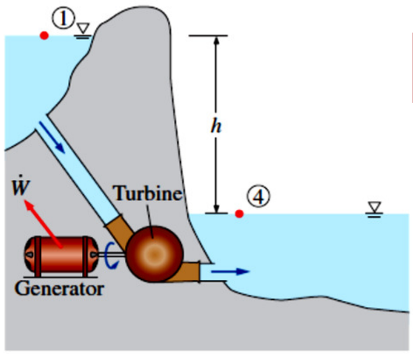
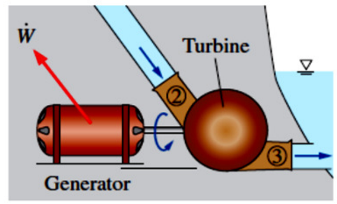
Mechanical Energy



The maximum (ideal) power generated by a turbine is $\dot{W} = \dot{E} = \dot{m}\Delta e_{mech}$ (KW)



$$\dot{W}_{max} = \dot{m}\Delta e_{mech} = \dot{m}g(z_1 - z_4) = \dot{m}gh$$

since $P_1 \approx P_4 = P_{atm}$ and $V_1 = V_4 \approx 0$

(*a*)

$$\dot{W}_{max} = \dot{m}\Delta e_{mech} = \dot{m}\frac{P_2 - P_3}{\rho} = \dot{m}\frac{\Delta P}{\rho}$$

since $V_2 \approx V_3$ and $z_2 = z_3$

(*b*)

Mechanical energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator. In the absence of irreversible losses, the maximum produced power is proportional to (a) the change in water surface elevation from the upstream to the downstream reservoir or (b) (close-up view) the drop in water pressure from just upstream to just downstream of the turbine

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EXAMPLE 2–2 **Wind Energy**

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s (Fig. 2–13). Determine the wind energy (*a*) per unit mass, (*b*) for a mass of 10 kg, and (*c*) for a flow rate of 1154 kg/s for air.

SOLUTION A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

Assumptions Wind flows steadily at the specified speed.

Analysis The only harvestable form of energy of atmospheric air is the kinetic energy, which is captured by a wind turbine.

(a) Wind energy per unit mass of air is

$$e = \text{ke} = \frac{V^2}{2} = \frac{(8.5\ \text{m/s})^2}{2}\left(\frac{1\ \text{J/kg}}{1\ \text{m}^2/\text{s}^2}\right) = \mathbf{36.1\ J/kg}$$

(b) Wind energy for an air mass of 10 kg is

$$E = me = (10\ \text{kg})(36.1\ \text{J/kg}) = \mathbf{361\ J}$$

(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154\ \text{kg/s})(36.1\ \text{J/kg})\left(\frac{1\ \text{kW}}{1000\ \text{J/s}}\right) = \mathbf{41.7\ kW}$$

Discussion It can be shown that the specified mass flow rate corresponds to a 12-m diameter flow section when the air density is 1.2 kg/m³. Therefore, a wind turbine with a wind span diameter of 12 m has a power generation potential of 41.7 kW. Real wind turbines convert about one-third of this potential to electric power.

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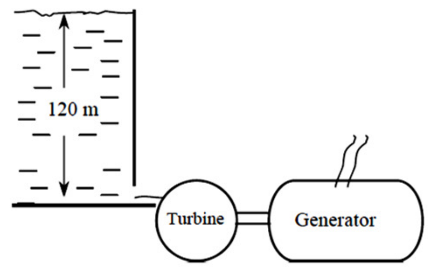
Example 2

Electric power is to be generated by installing a hydraulic turbine–generator at a site $120\ m$ below the free surface of a large water reservoir that can supply water at a rate of $1500\ kg/s$ steadily. Determine the power generation potential.

Answer:

Analysis The total mechanical energy water in a reservoir possesses is equivalent to the potential energy of water at the free surface, and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate.



$$e_{\text{mech}} = pe = gz = (9.81\ \text{m/s}^2)(120\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 1.177\ \text{kJ/kg}$$

Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (1500\ \text{kg/s})(1.177\ \text{kJ/kg})\left(\frac{1\ \text{kW}}{1\ \text{kJ/s}}\right) = \mathbf{1766\ kW}$$

Therefore, the reservoir has the potential to generate 1766 kW of power.

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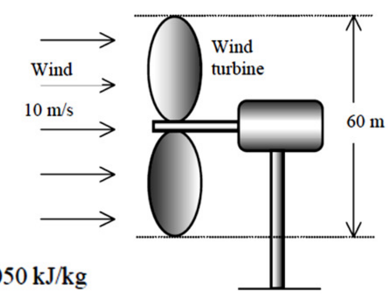
Example 3

At a certain location, wind is blowing steadily at $10\ m/s$. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 60-m-diameter blades at that location. Take the air density to be $1.25\ kg/m^3$.

Answer:

Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:



$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(10\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.050\ \text{kJ/kg}$$

$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\ \text{kg/m}^3)(10\ \text{m/s})\frac{\pi(60\ \text{m})^2}{4} = 35{,}340\ \text{kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (35{,}340\ \text{kg/s})(0.050\ \text{kJ/kg}) = \mathbf{1770\ \ kW}$$

Therefore, 1770 kW of actual power can be generated by this wind turbine at the stated conditions.

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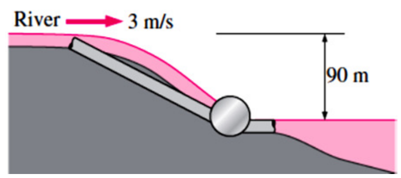
Example 4

Consider a river flowing toward a lake at an average velocity of $3\ m/s$ at a rate of $500\ m^3/s$ at a location $90\ m$ above the lake surface. Determine the total mechanical energy of the river water per unit mass and the power generation potential of the entire river at that location.



Answer:

$$e_{\text{mech}} = pe + ke = gh + \frac{V^2}{2} = \left((9.81\ \text{m/s}^2)(90\ \text{m}) + \frac{(3\ \text{m/s})^2}{2}\right)\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.887\ \text{kJ/kg}$$

The power generation potential of the river water is obtained by multiplying the total mechanical energy by the mass flow rate,

$$\dot{m} = \rho\dot{V} = (1000\ \text{kg/m}^3)(500\ \text{m}^3/\text{s}) = 500{,}000\ \text{kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (500{,}000\ \text{kg/s})(0.887\ \text{kJ/kg}) = 444{,}000\ \text{kW} = \mathbf{444\ MW}$$

Therefore, 444 MW of power can be generated from this river as it discharges into the lake if its power potential can be recovered completely.

Discussion Note that the kinetic energy of water is negligible compared to the potential energy, and it can be ignored in the analysis. Also, the power output of an actual turbine will be less than 444 MW because of losses and inefficiencies.

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Example 5

A person gets into an elevator at the lobby level of a hotel together with his $30\ kg$ suitcase, and gets out at the 10^{th} floor $35\ m$ above. Determine the amount of energy consumed by the motor of the elevator that is now stored in the suitcase.

Answer:

Analysis The energy stored in the suitcase is stored in the form of potential energy, which is mgz. Therefore,

$$\Delta E_{\text{suitcase}} = \Delta PE = mg\Delta z = (30\ \text{kg})(9.81\ \text{m/s}^2)(35\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{10.3\ kJ}$$

Therefore, the suitcase on 10^{th} floor has 10.3 kJ more energy compared to an identical suitcase on the lobby level.

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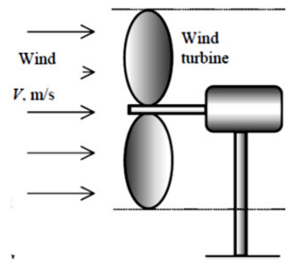
Example 6

Two sites are being considered for wind power generation. In the first site, the wind blows steadily at $7\ m/s$ for 3000 hours per year, whereas in the second site the wind blows at $10\ m/s$ for 2000 hours per year. Assuming the wind velocity is negligible at other times for simplicity, determine which is a better site for wind power generation. *Hint:* Note that the mass flow rate of air is proportional to wind velocity. Take the air density to be $1.25\ kg/m^3$.

Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate. Considering a unit flow area (A = 1 m^2), the maximum wind power and power generation becomes



$$e_{\text{mech},1} = ke_1 = \frac{V_1^2}{2} = \frac{(7\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.0245\text{ kJ/kg}$$

$$e_{\text{mech},2} = ke_2 = \frac{V_2^2}{2} = \frac{(10\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.050\text{ kJ/kg}$$

$$\dot{W}_{\text{max},1} = \dot{E}_{\text{mech},1} = \dot{m}_1 e_{\text{mech},1} = \rho V_1 A ke_1 = (1.25\text{ kg/m}^3)(7\text{ m/s})(1\text{ m}^2)(0.0245\text{ kJ/kg}) = 0.2144\text{ kW}$$

$$\dot{W}_{\text{max},2} = \dot{E}_{\text{mech},2} = \dot{m}_2 e_{\text{mech},2} = \rho V_2 A ke_2 = (1.25\text{ kg/m}^3)(10\text{ m/s})(1\text{ m}^2)(0.050\text{ kJ/kg}) = 0.625\text{ kW}$$

since 1 kW = 1 kJ/s. Then the maximum electric power generations per year become

$$E_{\text{max},1} = \dot{W}_{\text{max},1}\Delta t_1 = (0.2144\text{ kW})(3000\text{ h/yr}) = \mathbf{643\ kWh/yr}\ (\text{per m}^2\text{ flow area})$$

$$E_{\text{max},2} = \dot{W}_{\text{max},2}\Delta t_2 = (0.625\text{ kW})(2000\text{ h/yr}) = \mathbf{1250\ kWh/yr}\ (\text{per m}^2\text{ flow area})$$

Therefore, **second site** is a better one for wind generation.

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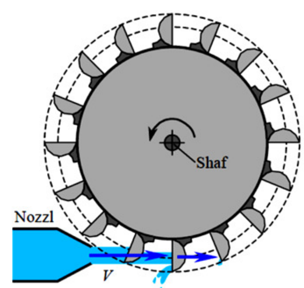
Example 7

A water jet that leaves a nozzle at $60\ m/s$ at a flow rate of $120\ kg/s$ is to be used to generate power by striking the buckets located on the perimeter of a wheel. Determine the power generation potential of this water jet.

Answer:



Analysis Kinetic energy is the only form of harvestable mechanical energy the water jet possesses, and it can be converted to work entirely. Therefore, the power potential of the water jet is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(60\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 1.8\text{ kJ/kg}$$

$$\dot{W}_{\text{max}} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}}$$

$$= (120\text{ kg/s})(1.8\text{ kJ/kg})\left(\frac{1\text{ kW}}{1\text{ kJ/s}}\right) = \mathbf{216\ kW}$$

Therefore, 216 kW of power can be generated by this water jet at the stated conditions

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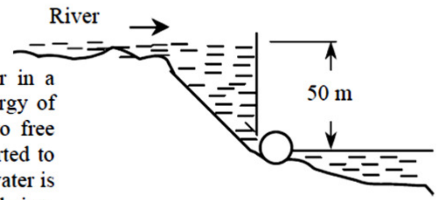
Example 8

A river flowing steadily at a rate of $240\ m^3/s$ is considered for hydroelectric power generation. It is determined that a dam can be built to collect water and release it from an elevation difference of $50\ m$ to generate power. Determine how much power can be generated from this river water after the dam is filled.



Answer:

Analysis The total mechanical energy the water in a dam possesses is equivalent to the potential energy of water at the free surface of the dam (relative to free surface of discharge water), and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate.

$$e_{\text{mech}} = pe = gz = (9.81\,\text{m/s}^2)(50\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 0.4905\,\text{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \rho\dot{V} = (1000\,\text{kg/m}^3)(240\,\text{m}^3/\text{s}) = 240{,}000\,\text{kg/s}$$

Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (240{,}000\,\text{kg/s})(0.4905\,\text{kJ/kg})\left(\frac{1\,\text{MW}}{1000\,\text{kJ/s}}\right) = \mathbf{118\ MW}$$

Therefore, 118 MW of power can be generated from this river if its power potential can be recovered completely.

Example 9

Water is pumped from a 200-ft-deep well into a 100-ft-high storage tank. Determine the power, in kW, that would be required to pump 200 gallons per minute. Take the density of the water $62.4\ lbm/ft^3$.

Answer:

Properties The density of water is taken to be 62.4 lbm/ft^3 (Table A-3E).

Analysis The required power is determined from

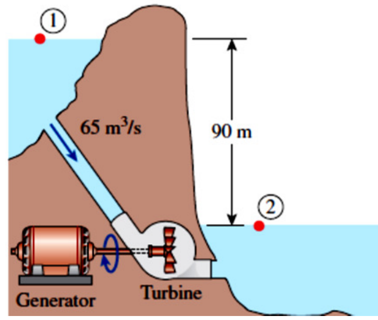
$$\dot{W} = \dot{m}g(z_2 - z_1) = \rho\dot{V}g(z_2 - z_1)$$

$$= (62.4\,\text{lbm/ft}^3)(200\,\text{gal/min})\left(\frac{35.315\,\text{ft}^3/\text{s}}{15{,}850\,\text{gal/min}}\right)(32.174\,\text{ft/s}^2)(300\,\text{ft})\left(\frac{1\,\text{lbf}}{32.174\,\text{lbm}\cdot\text{ft/s}^2}\right)$$

$$= 8342\,\text{lbf}\cdot\text{ft/s} = (8342\,\text{lbf}\cdot\text{ft/s})\left(\frac{1\,\text{kW}}{737.56\,\text{lbf}\cdot\text{ft/s}}\right) = \mathbf{11.3 kW}$$

Example 10

A hydroelectric power plant, $65\ m^3/s$ of water flows from an elevation of $90\ m$ to a turbine, where electric power is generated. Disregarding frictional losses in piping, estimate the **electric power output** of this plant.



Analysis: The total mechanical energy the water in a dam possesses is equivalent to the potential energy of water at the free surface of the dam (relative to free surface of discharge water), and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate.

$$e_{mech} = pe = gz = (9.81\,\text{m/s}^2)(90\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 0.8829\,\text{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \rho\dot{V} = (1000\,\text{kg/m}^3)(65\,\text{m}^3/\text{s}) = 65{,}000\,\text{kg/s}$$

Then the maximum and actual electric power generation become

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech} = (65{,}000\,\text{kg/s})(0.8829\,\text{kJ/kg})\left(\frac{1\,\text{MW}}{1000\,\text{kJ/s}}\right) = 57.39\,\text{MW}$$

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