ESO 201A: Thermodynamics

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Energy and Energy Transfer-part 4

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Learning objectives

- 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.
- Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.
- Define energy conversion efficiencies.

Energy efficiency

Water heater

Efficiency- how well an energy conversion or transfer is accomplished

$$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}}$$

Efficiency of a water heater: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.

Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

Energy conversion efficiency

Why gas based water heater has a low efficiency?

- Efficiency of equipment that involves the combustion of a fuel is based on the heating value of the fuel.

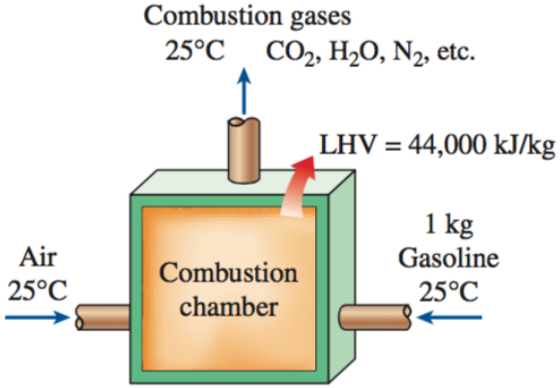
Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

Combustion efficiency.

$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$



Energy conversion efficiency

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:** The ratio of the net shaft work output to the heat input to the working fluid.

Overall efficiency of a power plant

net electrical work power output to the rate of fuel energy input

$$\eta_{\text{overall}} = \eta_{\text{combustion}}\,\eta_{\text{thermal}}\,\eta_{\text{generator}} = \frac{W_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{fuel}}}$$

Energy conversion efficiency

TABLE 2–2

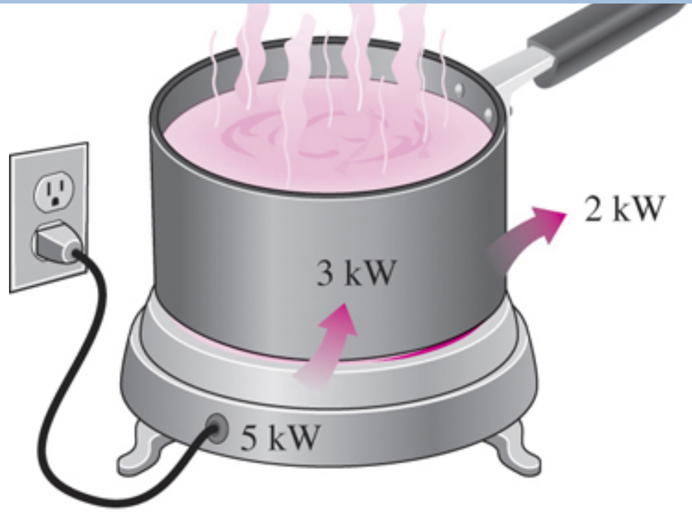
Energy costs of cooking a casserole with different appliances*

[From A. Wilson and J. Morril, *Consumer Guide to Home Energy Savings*, Washington, DC: American Council for an Energy-Efficient Economy, 1996, p. 192.]

Cooking appliance	Cooking temperature	Cooking time	Energy used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	$0.16
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	$0.11
Gas oven	350°F (177°C)	1 h	0.112 therm	$0.07
Frying pan	420°F (216°C)	1 h	0.9 kWh	$0.07
Toaster oven	425°F (218°C)	50 min	0.95 kWh	$0.08
Electric slow cooker	200°F (93°C)	7 h	0.7 kWh	$0.06
Microwave oven	"High"	15 min	0.36 kWh	$0.03

*Assumes a unit cost of $0.08/kWh for electricity and $0.60/therm for gas.

- Using energy-efficient appliances conserve energy.
- It helps the **environment** by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces
    - carbon dioxide, causes global warming
    - nitrogen oxides and hydrocarbons, cause smog
    - carbon monoxide, toxic
    - sulfur dioxide, causes acid rain.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}} = \frac{3 \text{ kWh}}{5 \text{ kWh}} = 0.60$$

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

Efficiency of mechanical and electric devices

The transfer of mechanical energy is usually accompanied by rotation shaft.
Thus mechanical work is often referred as shaft work.

- A pump or fan receive shaft work usually from an electric motor and transfer it to fluid as mechanical energy.

- A turbine converts the mechanical energy of a fluid to a shaft work
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- In absence of any frictional losses, mechanical energy can be converted entirely to another form of mechanical energy.

- Less than 100 % efficiency mean some has converted to thermal energy (losses)

Mechanical efficiency

$$\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{\text{mech, out}}}{E_{\text{mech, in}}} = 1 - \frac{E_{\text{mech, loss}}}{E_{\text{mech, in}}}$$

Efficiency of mechanical and electric devices

In a fluid system, interest is to increase the pressure, velocity or elevation of a fluid

- Achieved by supplying mechanical energy to the fluid by
  - Pump, fan, or a compressor

$$\eta_{\text{pump}} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

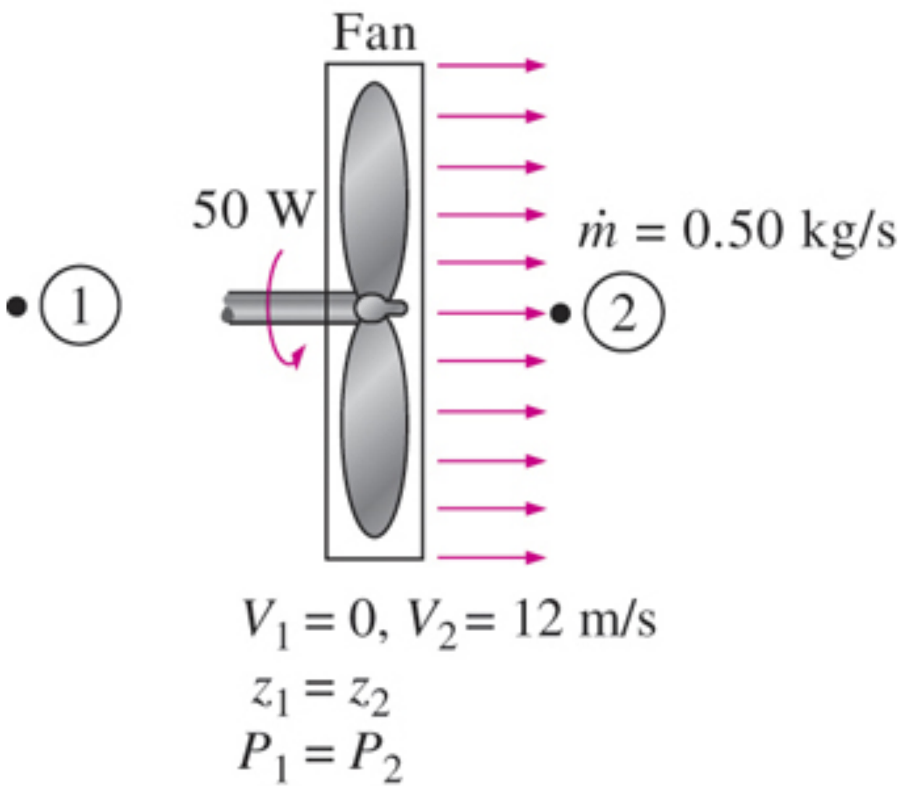
$$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$$

Alternatively, we would like extract mechanical energy of a fluid by a turbine and produce mechanical power in the form of rotating shaft that can drive a generator

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{\text{shaft, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

$$|\Delta \dot{E}_{\text{mech,fluid}}| = \dot{E}_{\text{mech,in}} - \dot{E}_{\text{mech,out}}$$

Efficiency of mechanical and electric devices



$$\eta_{\text{mech, fan}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{\text{shaft,in}}}$$

$$= \frac{(0.50 \text{ kg/s})(12 \text{ m/s})^2/2}{50 \text{ W}}$$

$$= 0.72$$

The mechanical efficiency of a fan is the ratio of the kinetic energy of air at the fan exit to the mechanical power input.

Efficiency of mechanical and electric devices

Mechanical efficiency is not to confused with motor efficiency and the generator efficiency:

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft, out}}}{\dot{W}_{\text{elect, in}}}$$

Motor efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{shaft, in}}}$$

Generator efficiency

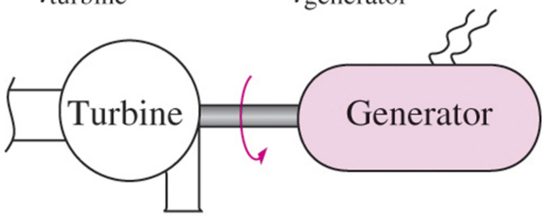
$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump}, u}}{\dot{W}_{\text{elect, in}}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{elect, in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{turbine}, e}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|}$$

Turbine-Generator overall efficiency

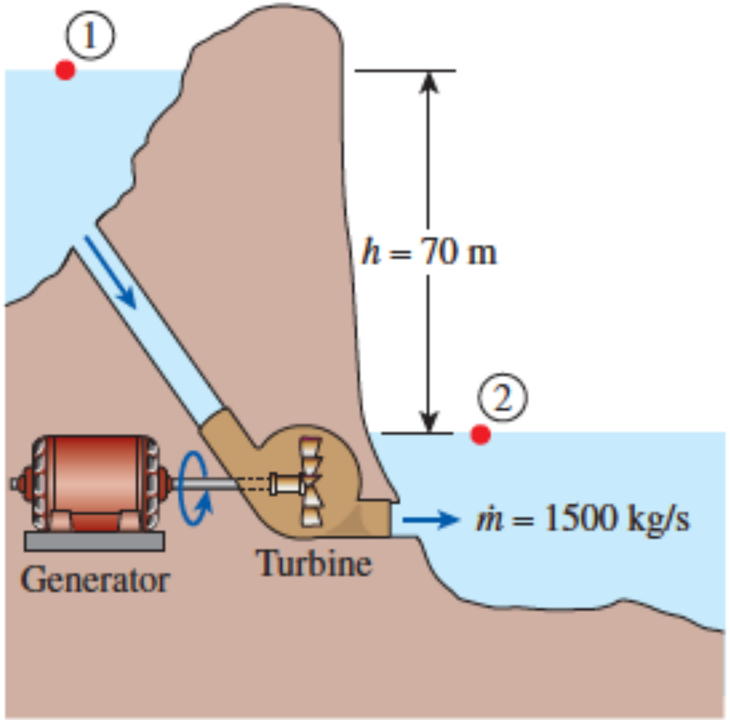
$\eta_{\text{turbine}} = 0.75$ $\eta_{\text{generator}} = 0.97$



$$\begin{aligned}\eta_{\text{turbine-gen}} &= \eta_{\text{turbine}}\eta_{\text{generator}} \\ &= 0.75 \times 0.97 \\ &= 0.73\end{aligned}$$

The overall efficiency of a turbine–generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical energy of the fluid converted to electric energy.

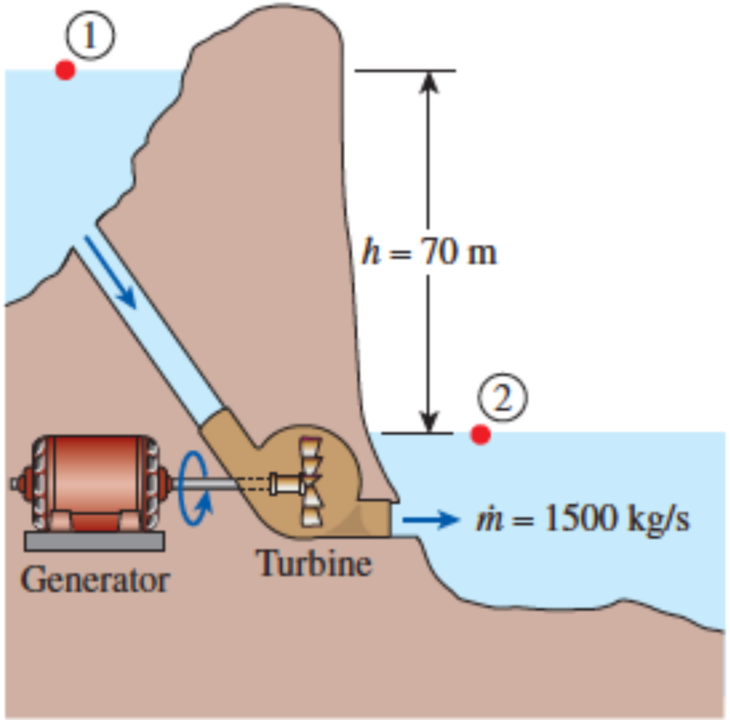
Turbine-generator efficiency



Electric power is to be generated by installing a hydraulic turbine-generator at a site 70 m below the free-surface of a large reservoir, that can supply water at a steady rate 1500 kg/s. If the mechanical power output of the turbine is 800 kW and the electric power generator is 750 kW, determine the turbine efficiency, and combine turbine-generator efficiency

Neglect losses in the pipe

Turbine-generator efficiency



Neglect losses in the pipe

z_2=0 (reference)

pe_1=gz_1

pe_2=0

P_1=P_2=P_{atm}

Thus flow energy P/ρ is zero

ke 1 =0 , motionless

ke 2~0 , considered negligible

$$\text{pe}_1 = gz_1 = (9.81 \text{ m/s}^2)(70 \text{ m})\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 0.687 \text{ kJ/kg}$$

Rate of mechanical energy of water supplied to the turbine

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = \dot{m}(\text{pe}_1 - 0) = \dot{m}\text{pe}_1$$

$$= (1500 \text{ kg/s})(0.687 \text{ kJ/kg})$$

$$= 1031 \text{ kW}$$

Turbine-generator efficiency

Turbine-gen efficiency

$$\eta_{\text{turbine}-\text{gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{750 \text{ kW}}{1031 \text{ kW}} = \mathbf{0.727} \quad \text{or} \quad \mathbf{72.7\%}$$

Turbine efficiency

$$\eta_{\text{turbine}} = \frac{W_{shaft,out}}{\left|\dot{E}_{mech,fluid}\right|} = \frac{800 \text{ kW}}{1031 \text{ kW}} = 0.776 \text{ or } 77.6\ \%$$

Reservoir supplies 1031 kW of mechanical energy to the turbine, which converts 800 kW of it to shaft work that drive the generates 750 kW of electric power!

Summary

- Forms of energy
  - Macroscopic = kinetic + potential
  - Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- Energy transfer by heat
- Energy transfer by work
- Mechanical forms of work
- The first law of thermodynamics
  - Energy balance
  - Energy change of a system
  - Mechanisms of energy transfer (heat, work, mass flow)
- Energy conversion efficiencies
  - Efficiencies of mechanical and electrical devices (turbines, pumps)