Energy Management & Utilization

Chapter 2

Energy Fundamentals

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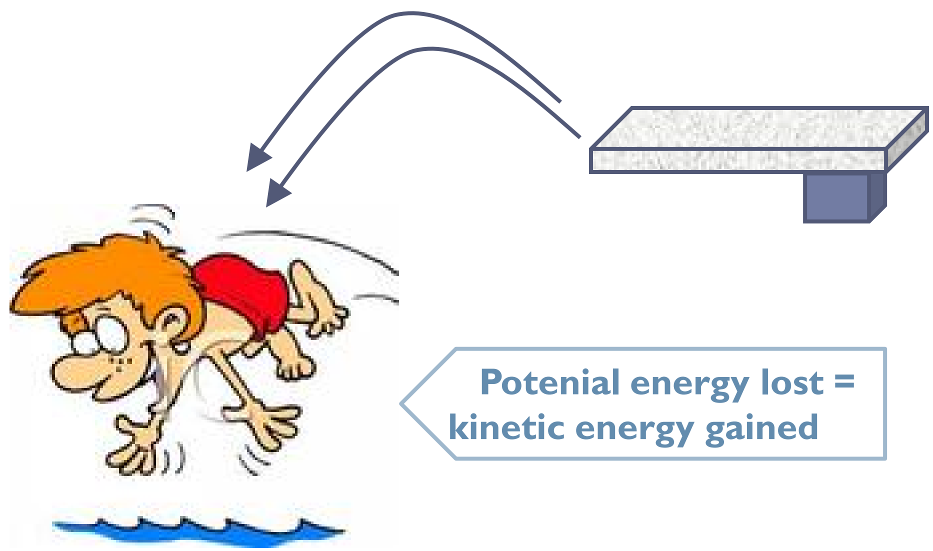
Conservation of Energy Principle (First Law of Thermodynamics)

What is conservation of energy?
It simply states that during a prosess, energy can change from one state to another but that the total amount of energy remains constant. (Energy can not be created or destroyed)



Basic Dimensions and their Units

Basic dimensions	Mass(m)	Length(L)	Time(t)
SI units	Kilogram (kg)	Meter (m)	Second (s)
English units	Pound-mass (lbm)	Foot (ft)	Second (s or sec)

1 lbm = 0.45359 kg

1 ft = 0.3048 m

Units Derived from Basic Dimensions

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$F = m\left(\text{kg}\right) \times a\left(\text{m}/\text{s}^2\right)$$ In SI units the unit for force in Newtons (N)

In English units, Pound - force (lbf)

$$\text{Work} = \text{Force} \times \text{Distance}$$

$$W = F\,(\text{N}) \times d\,(\text{m})$$ In SI units the unit of work is Joules (J)

In English units, British Thermal Units (Btu)

Energy has the same units as Work.

$$1\,\text{Btu} = 1.055\,\text{kJ}$$

Forms of Energy

- thermal, mechanical, kinetic, potential, electric, magnetic, chemical, nuclear
- Total energy in a process:

$$E = \text{the sum of all forms of energy}$$

- Thermodynamics deals with the change of energy instead of its absolute value.
- It is appropriate to assign the total energy of a system a value of zero (E=0) at some convenient reference point.

Forms of Energy

KINETIC ENERGY

$$KE = \frac{m \times \upsilon^2}{2} \qquad (\text{kJ})$$

Rate of kinetic energy :

$$\dot{KE} = \frac{\dot{m} \times \upsilon^2}{2} \qquad (\text{kJ/s} \equiv \text{kW})$$

POTENTAL ENERGY

$$PE = m \times g \times z \quad (\text{kJ})$$

Rate of potential energy :

$$\dot{PE} = \dot{m} \times g \times z \quad (\text{kJ/s} \equiv \text{kW})$$

INTERNAL ENERGY

U (kJ)

Is related to the degree of molecular activity in a system.

$$U = m \times C_v \times \Delta T$$

Nomencature :

KE : kinetic energy (kJ)

PE : potential energy (kJ)

U : internal energy (kJ)

m : mass (kg)

$\dot{m}$: mass flow rate (kg/s)

υ : velocity (m/s)

g : gravitational acceleration (m/s^2)

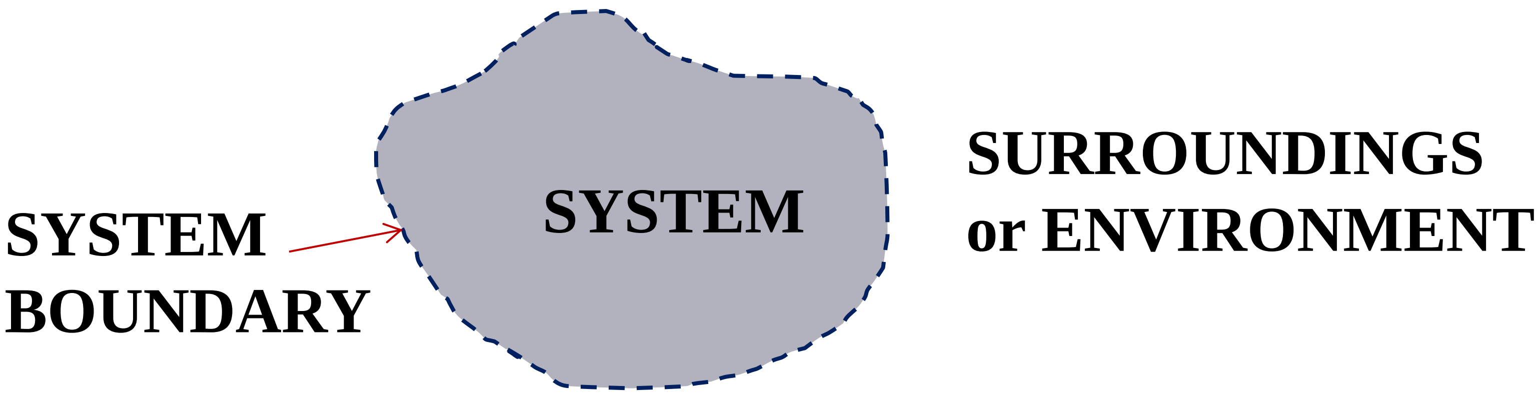
z : elevation from a reference point (m)

C_v : specific heat capacity at constant volume (kJ/kgK)

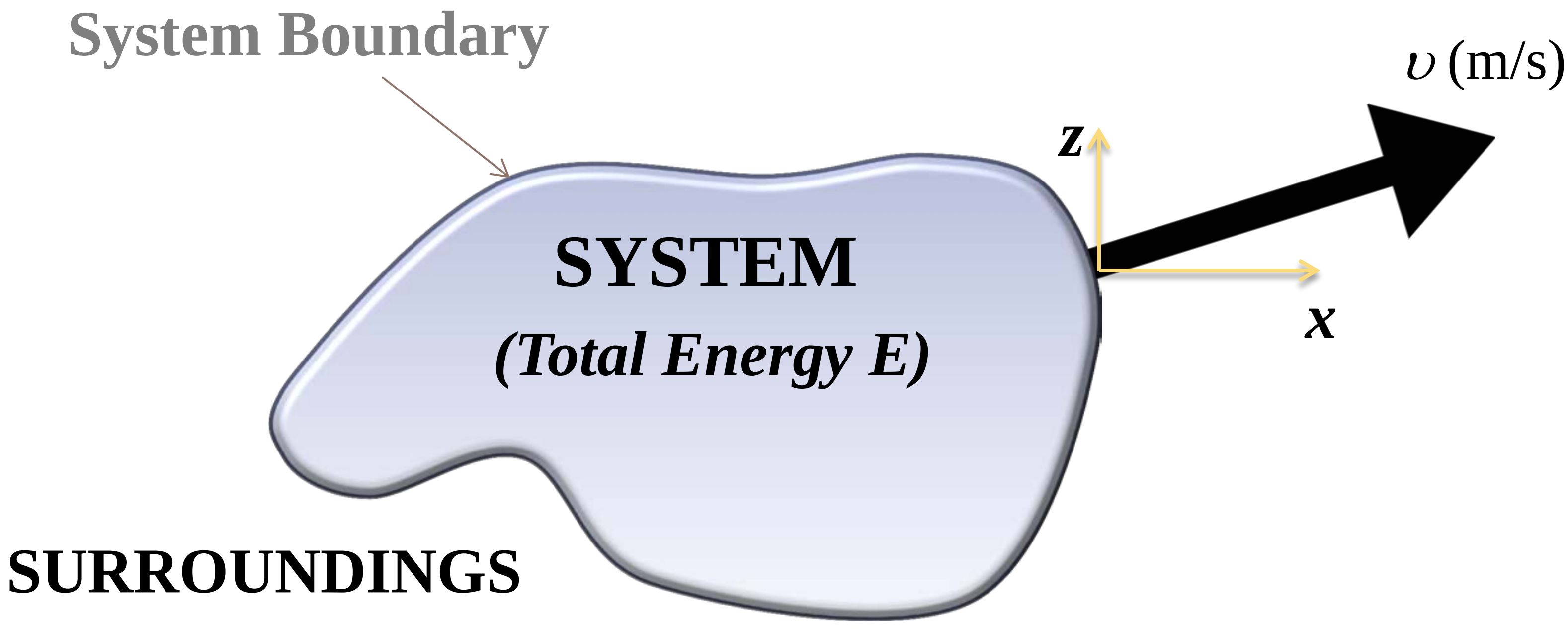
T : Temperature

Defining a System

- By defining a system we establish the *surroundings* of the system.
- The surface that separates the system from the surroundings is known as the *boundary*.



Thermodynamic System

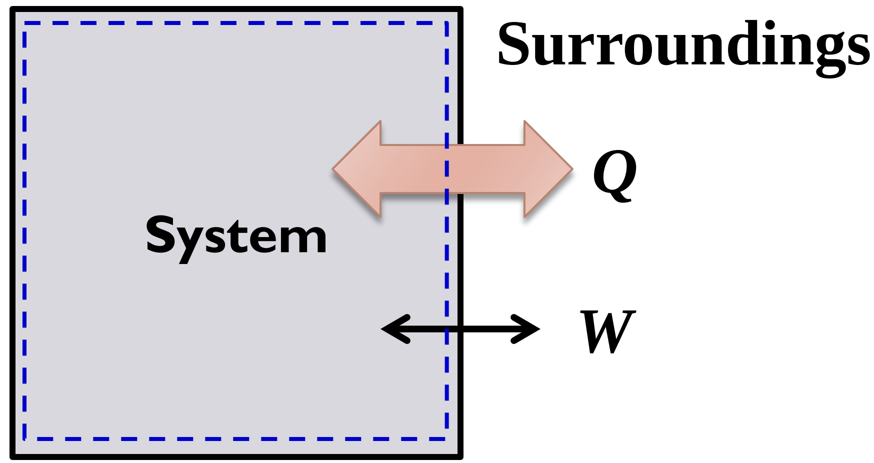


$$E = \text{the sum of all forms of energy}$$

$$E = U + KE + PE = U + \frac{m\upsilon^2}{2} + mgz \quad \text{(kJ)}$$

Closed Systems

- Energy can cross the boundary in two forms: *Heat* and *work*.
- *Mass* of the system is constant.



{ Net energy transfer to (or from) the system as heat and work } = { Net increase (or decrease) in the total energy of the system }

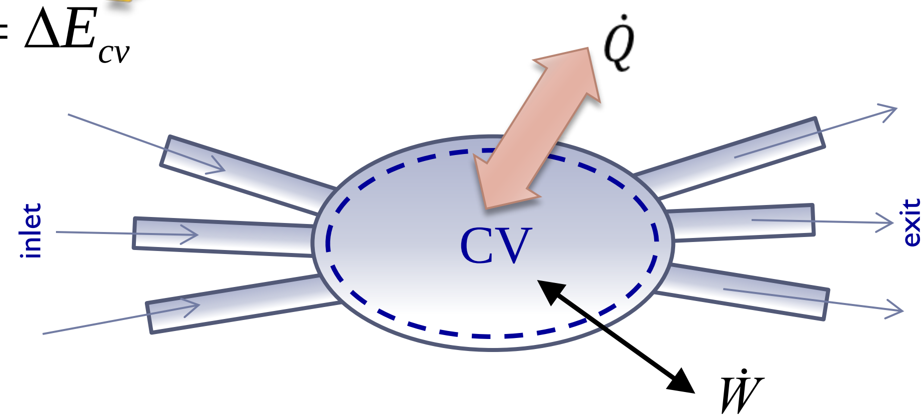
$$Q - W = \Delta E = \Delta U + \Delta KE + \Delta PE$$

$$= (U_2 - U_1) + \frac{m(\upsilon_2^2 - \upsilon_1^2)}{2} + mg(z_2 - z_1) \quad \text{(kJ)}$$

Energy Equation for Open Systems

$$\left\{\begin{array}{l}\text{Total energy}\\ \text{crossing boundary}\\ \text{as heat and work}\end{array}\right\} + \left\{\begin{array}{l}\text{Total energy of}\\ \text{mass entering the}\\ \text{control volume}\end{array}\right\} - \left\{\begin{array}{l}\text{Total energy of}\\ \text{mass leaving the}\\ \text{control volume}\end{array}\right\} = \left\{\begin{array}{l}\text{Net change}\\ \text{in Energy of}\\ \text{control volume}\end{array}\right\}$$

$$Q - W + \sum E_{in} - \sum E_{out} = \Delta E_{cv}$$



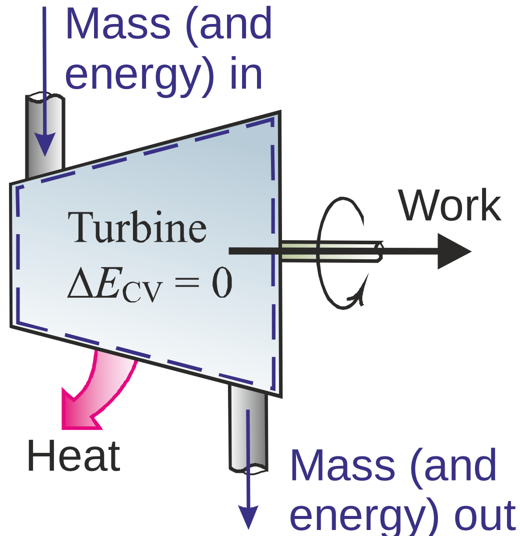
Steady flow energy equation

$$E_{CV} = \text{constant} \quad \text{or} \quad \Delta E_{CV} = 0$$

i = inlet, e = exit

$$\Rightarrow \dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e\right) - \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i\right)$$

Energy Equation for Open Systems



Ex: STEAM TURBINE

Conservation of mass principle for steady flow:

$$\rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}$$

Steady flow energy equation for single stream flow:

$$\rightarrow \dot{Q} - \dot{W} = \dot{m}\left\{(h_2 - h_1) + \frac{{v_2}^2 - {v_1}^2}{2} + g(z_2 - z_1)\right\}$$

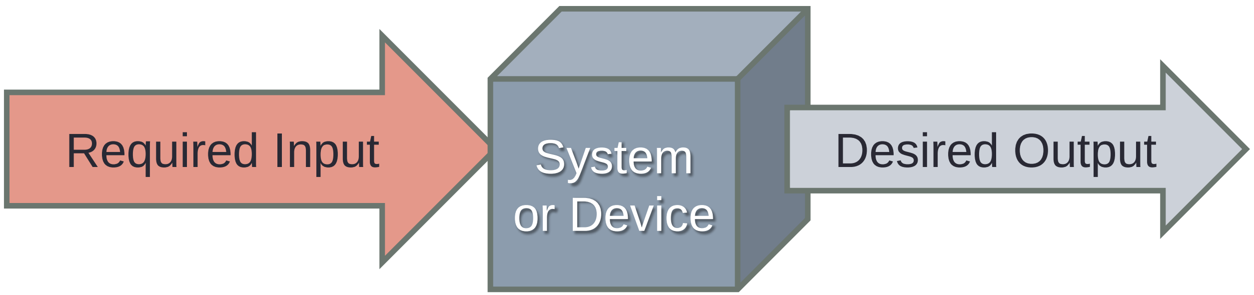
1 = inlet, 2 = exit

Heat loss, kinetic energy and potential energy changes are negligible, therefore:

$$\rightarrow \dot{Q} - \dot{W} = \dot{m}\,(h_2 - h_1)$$

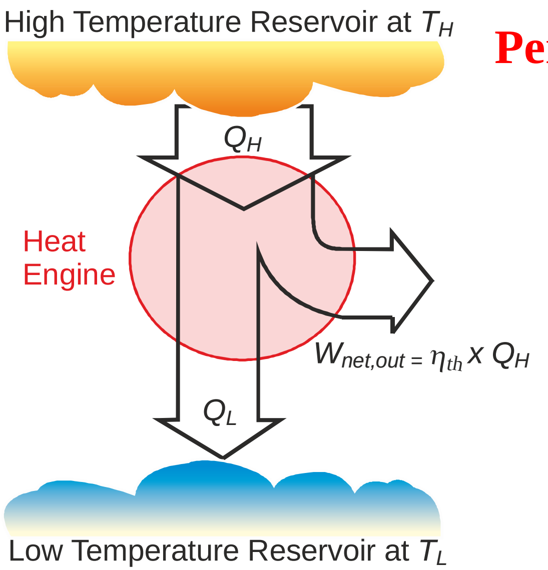
Performance of Engineering Devices

- General definition of performance:



$$\text{Performance} = \frac{\text{Desired Output}}{\text{Required Input}}$$

Thermal efficiency of heat engines



Performance = $\dfrac{\textbf{Desired output}}{\textbf{required input}}$ = $\dfrac{\textbf{What I Get}}{\textbf{What I pay for}}$

In heat engines:

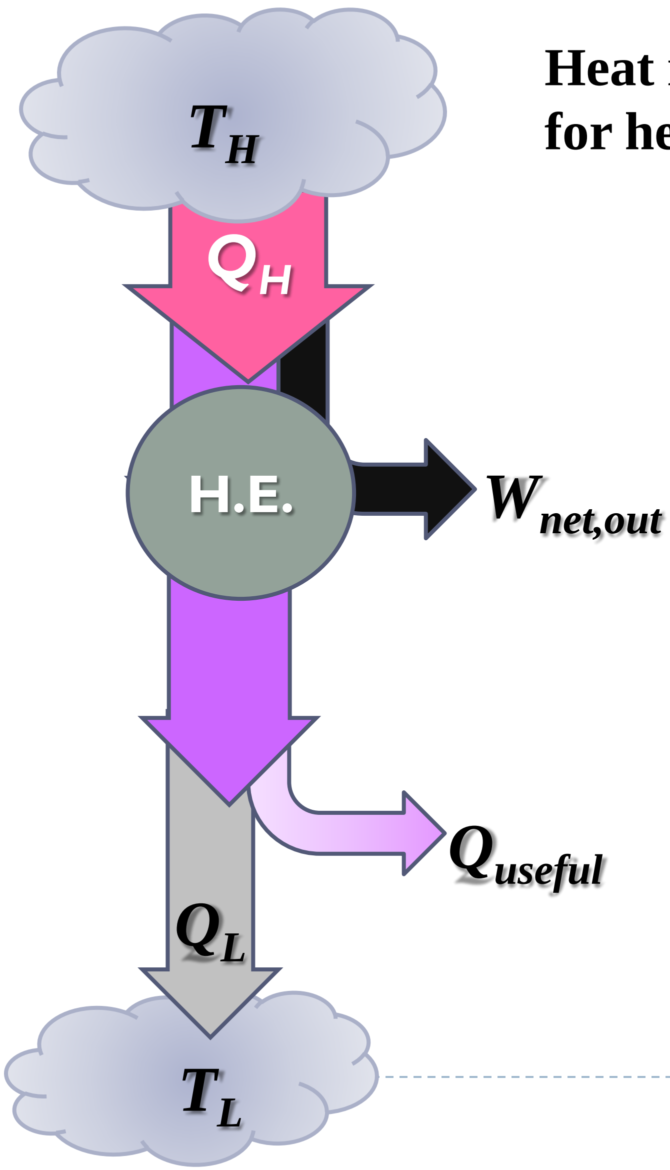
the desired output = net work output = $W_{net,out}$

the required input = heat supplied to system = Q_{in}

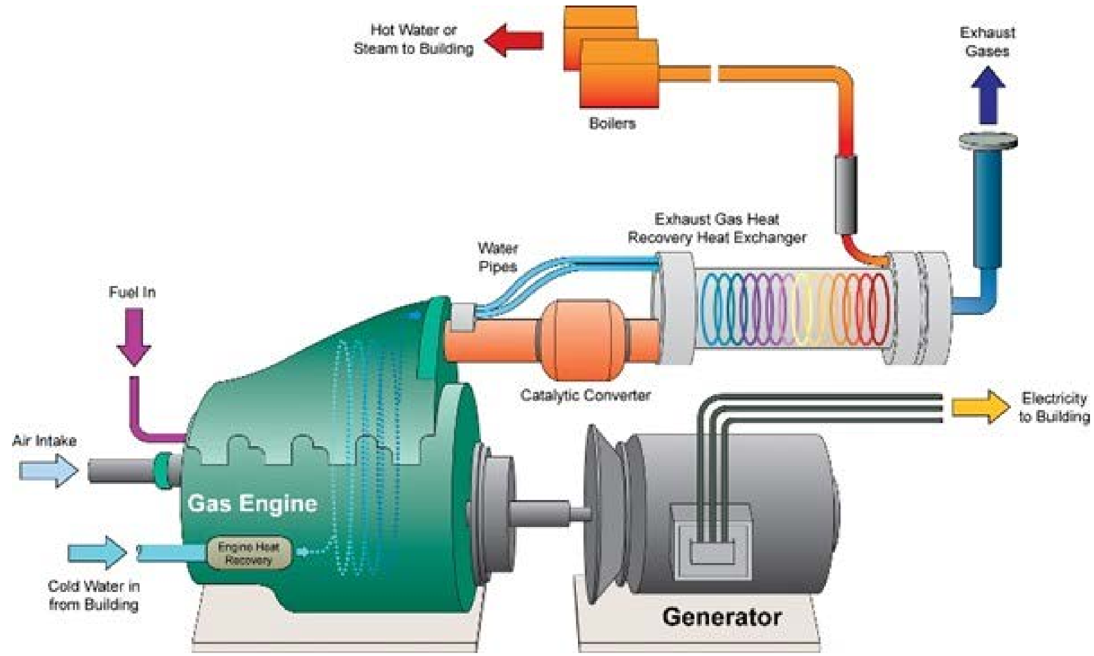
Thermal efficiency $\eta_{th} = \dfrac{W_{net,out}}{Q_{in}} = \dfrac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \dfrac{Q_{out}}{Q_{in}}$

or $\eta_{th} = \dfrac{W_{net,out}}{Q_H} = 1 - \dfrac{Q_L}{Q_H}$

Performance of Cogeneration Units



Heat rejection from a heat engine can be used for heating processes as well

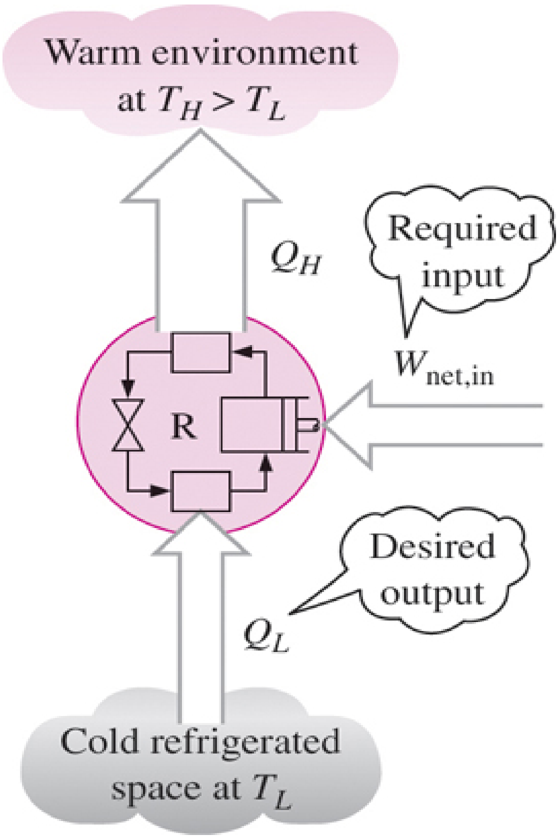


Energy Utilization Factor:

$$\varepsilon = \frac{W_{\text{net, out}} + Q_{\text{useful}}}{Q_{\text{H}}}$$

Coefficient of Performance (*COP*) of refrigerators

Refrigerators:



- **The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).**
- **The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.**

For a refrigerator $COP_R = \dfrac{\text{Desired output}}{\text{Required input}}$

$$= \frac{Q_L}{W_{net,in}} \left(or \; \frac{\dot{Q}_L}{\dot{W}_{net,in}} \right)$$

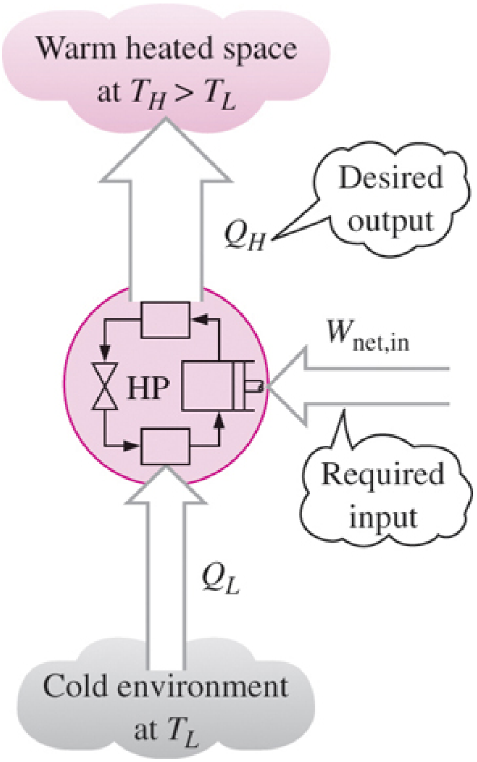
$$W_{net,in} = Q_H - Q_L \quad (\textbf{kJ})$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H / Q_L - 1}$$

Notice that COP_R, can be greater than unity.

Coefficient of Performance (*COP*) of heat pumps

Heat Pumps:



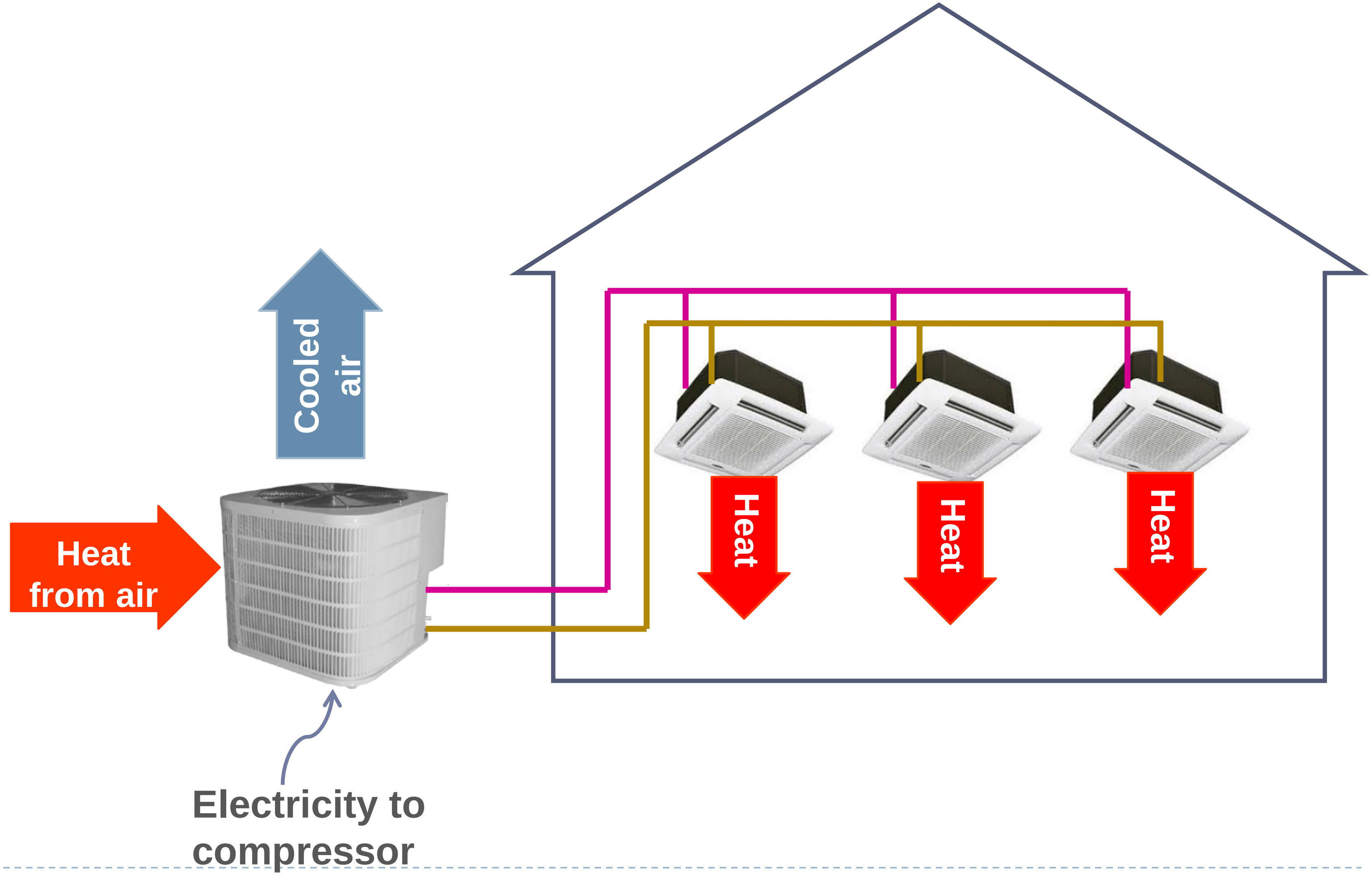
- **another device that transfer heat from T_L to T_H.**
- **objective is different : maintain a heated space at high temperature.**

$$COP_{HP} = \frac{\textbf{Desired output}}{\textbf{Required input}} = \frac{Q_H}{W_{net,in}}$$

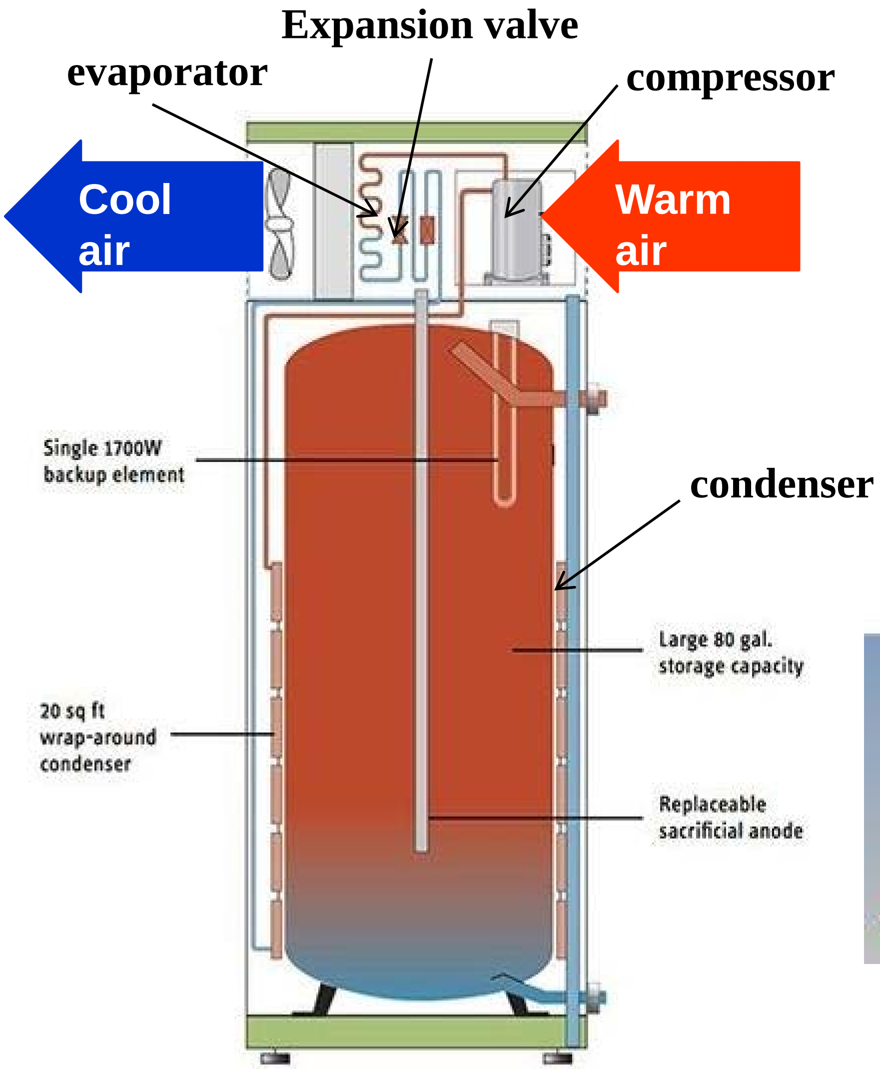
$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L / Q_H}$$

The objective of a heat pump is to supply heat Q_H into the warmer space.

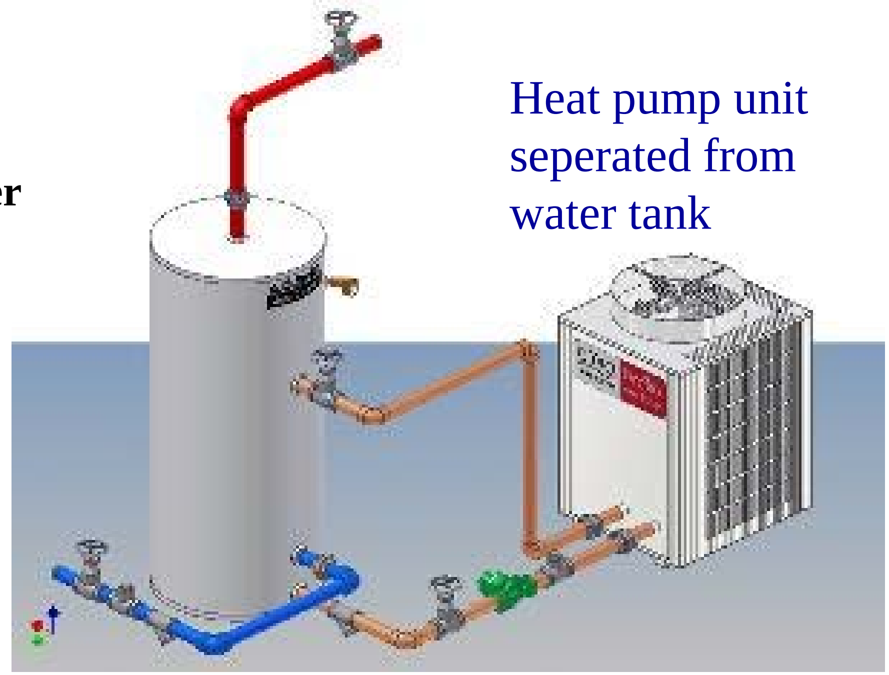
Air-to-Air Heat Pump



Air-to-Water Heat Pumps



In warm climates
COP: ~ 4 – 5



Heat pump unit seperated from water tank

Heat Pump Example

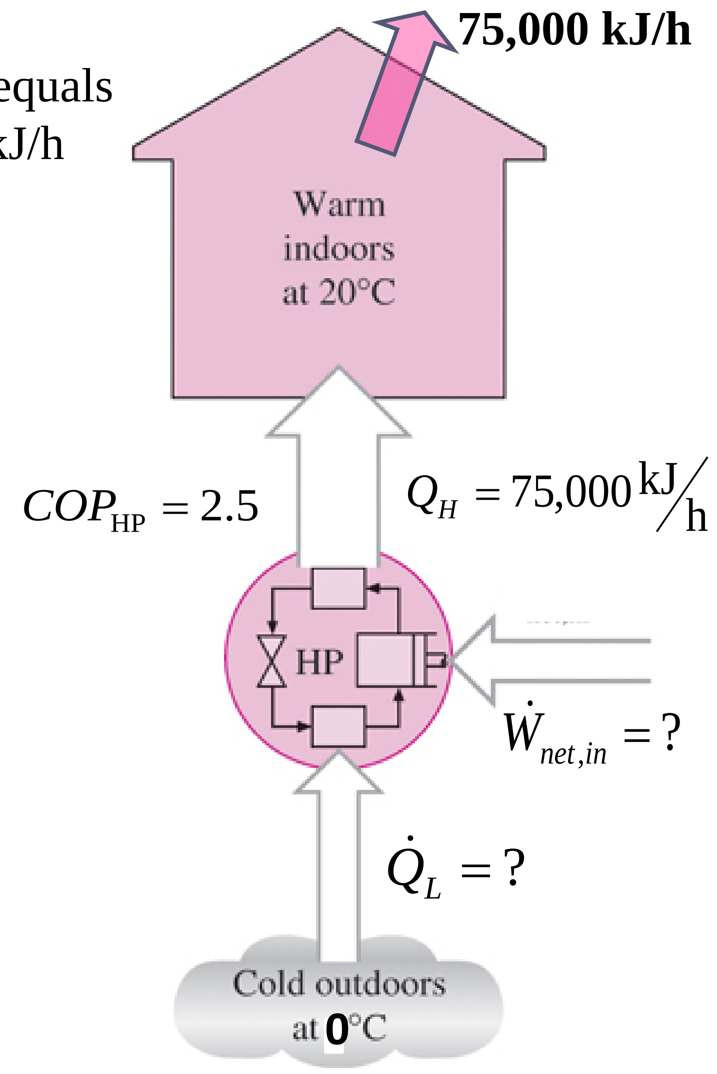
For constant indoor temperature it is required that Q_H equals heat losses from the building. Therefore Q_H = 75,000 kJ/h

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} \rightarrow \dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{75,000}{2.5}$$

$$\dot{W}_{net,in} = 30,000 \, \text{kJ/h} \text{ (or 8.33kW)}$$

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} = (75,000 - 30,000)$$

$$= 45,000 \, \text{kJ/h}$$

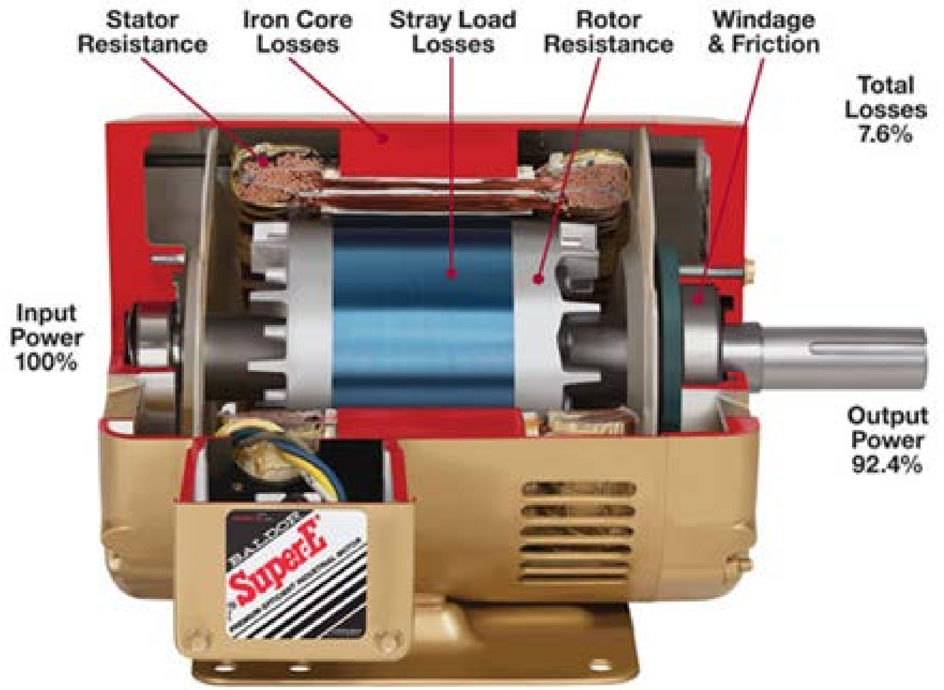


Efficiency of electric motors

- Efficiency (EFF) of a motor is defined as:

$$EFF = \frac{\text{Desired Output}}{\text{Required input}} = \frac{\text{Mechanical Power Output}}{\text{Electrical Power Input}}$$

Electrical power input →



→ **Mechanical power output**

Efficiency of electric motors

Many technological improvements have been made to electric motors. From new materials for inside windings to decreased friction from well-designed ball bearings, the efficiency of new motors increases almost every day.

Example

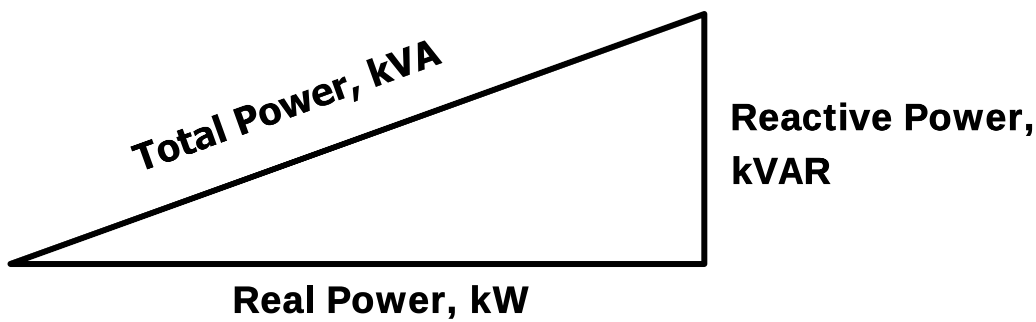
A motor delivers a shaft output power of 10 kW, and has an electrical power input of 12 kW. What is its efficiency?

Solution:

$$EFF = \frac{10\ kW}{12\ kW} = 83.3\%$$

Power factor of electric motors

- **Power Factor** – The power factor is an electrical operating parameter of a motor, and is found from the ratio of the real power input in kW to the total power input in kVA.



$$PF = \text{kW} / \text{kVA}$$

- Larger motors usually have higher power factors than smaller motors. Larger motors will usually have power factors around 85%.
- Sometimes, electrical capacitors are installed on motors to provide "power factor correction." This may be cost-effective for the facility if their utility charges a substantial penalty for low power factor.

Example

A three phase, 380 volt motor is drawing 80 amperes, and a real power of 40 kW. What is the power factor of the motor?

Solution

power drawn by a general three phase load:

$$P = \sqrt{3} \times V \times I \times PF \text{ watts}$$

$$40{,}000 = \sqrt{3} \times 380 \times 80 \times PF$$

$$PF = \frac{40{,}000}{52{,}653} = 76\,\%$$

Do not confuse the power factor with the motor load factor defined next.

Load factor of electric motors

- **Motor Load Factor** – The motor load factor is a mechanical operating parameter of a motor, and is found from the ratio of the actual shaft power being provided to the maximum shaft power that could be provided by the motor.
  - The maximum shaft power that can be provided is the nameplate hp rating of the motor.
  - The actual shaft power being provided to the load is determined by the load itself.

$$LF = \text{Actual shaft power} / \text{Maximum shaft power}$$

- A motor is what we call a "load driven device."
  - This means that the motor only provides the exact amount of power required by the load.
  - If the load on a 20 kW motor is a fan requiring only 10 kW to drive it, the load factor on the motor is 10kW/20kW, or 50%.
- The input power to the motor will only be what is needed to drive the actual load – and most often it will not be the full rated load power of the motor.
  - Typical motor load factors on an annual basis are in the range 40 – 60%.

Example

A 40 kW motor is connected to a 25 kW fan. What is the load factor of the motor?

Solution

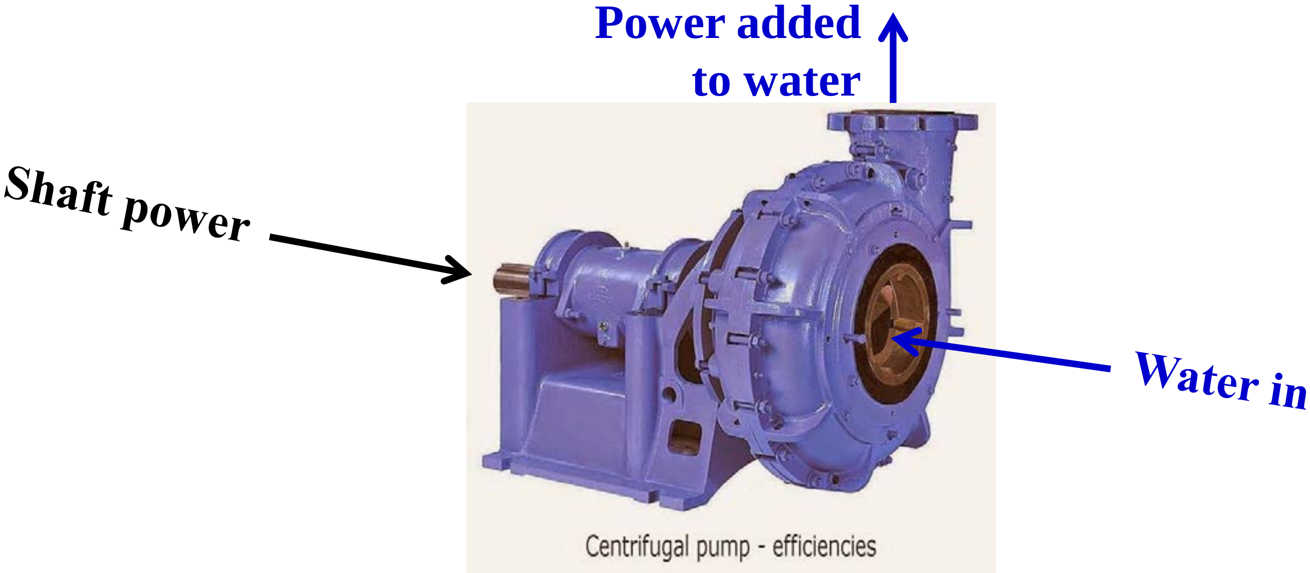
$$LF = \frac{25\,kW}{40\,kW} = 62.5\,\%$$

Do not confuse the motor load factor with the power factor defined above.

Water pump efficiency

- Defined as the ratio of power imparted on the water by the pump to the shaft power input for the pump
- Such that:

$$\text{Pump efficiency} = \frac{\text{Power conveyed to water}}{\text{Shaft power}}$$



Efficiency of pumping fluids

Pump brake horse power in kW

$$P = \frac{\text{flow rate (m}^3\text{/s)} \times \text{pressure difference (N/m}^2\text{)}}{1000 \times \text{efficiency}}$$

The overall pumping efficiency refers to both the pump and motor efficiencies :

Flow rate in m³/s

Pump head in N/m²

$$P = \frac{\dot{V} \times \Delta P}{1000 \times \eta_p \times \eta_m}$$

Pump power consumption in kW

Pump efficiency

Motor efficiency

Pump Example

Required capacity is 80 L/s with a head of 150 kN/m^2. What is the saving in power if a pump efficiency of 90% is preferred instead of 78%. Assume motor efficiency to be 100%.

Pump power :

$$P = \frac{\dot{V} \times \Delta P}{1000 \times \eta_p \times \eta_m}$$

Saving in pump power :

$$= \frac{(\dot{V} \times \Delta P)}{1000}\left(\frac{1}{\eta_{78\%}} - \frac{1}{\eta_{90\%}}\right) = \frac{0.08 \times 150 \times 10^3}{1000}\left(\frac{1}{0.78} - \frac{1}{0.9}\right) = 2.05\,\mathrm{kW}$$

The performance measure of electric lamps: «*Efficacy*»

- Efficacy is measured in units of lumens per watt (Lu/W).
- This is not a measure of efficiency since it has units.
  - Efficiency has no units, and is either expressed as a decimal number like 0.90, or is stated in percent, like 90 %.
  - Efficacy has units of Lu/W.

Example for efficacy

A 60 watt incandescent lamp has an output of 1100 lumens (amount of ight). What is the efficacy of this lamp?

The efficacy equals 1100 lumens divided by 60 watts

$$\text{Efficacy} = \frac{\text{Light output (lumens)}}{\text{Electricity required (Watts)}}$$

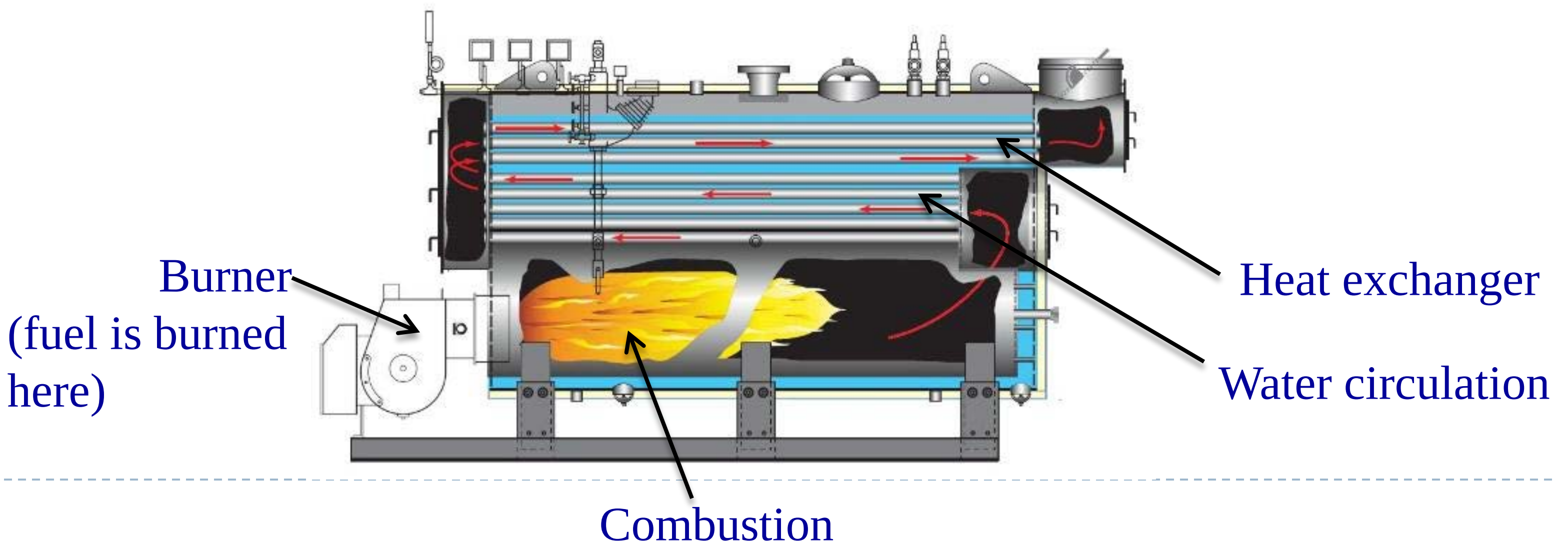
$$\text{Efficacy} = \frac{1100\ \text{lumens (Lu)}}{60\ \text{Watts (W)}} = 18.3\ \text{Lu/W}$$

Boiler Efficiency

- Boiler efficiency is a combined result of efficiencies of different components of a boiler. A boiler has many sub systems whose efficiency affects the overall boiler efficiency. Couple of efficiencies which finally decide the boiler efficiency are-

    1. **Combustion efficiency** (is the indication of burner's ability to burn fuel)
    2. **Thermal efficiency** (specifies the effectiveness of the heat exchanger of the boiler)

    Apart from these efficiencies, there are some other losses which also play a role while deciding the boiler efficiency and hence need to be considered while calculating the boiler efficiency.



Hot Water Generation with Central Boiler

- Hot water can be generated by the central boiler plant and stored