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MENG449
INTRODUCTION TO ENERGY MANAGEMENT

Chapter 2 – Energy Fundamentals

Coverage:

- Definition of thermodynamic system
- Heat transfer essentials
- Energy equation for closed systems
- Steady flow energy equation
- Thermal comfort
- Environmental impact of fuels
- Electric energy and power
- Unit conversions

Conservation of energy principle (First law of thermodynamics)

During a process, energy can change from one state to another but that the total amount of energy remains constant. (Energy can not be created or destroyed)

Diving action: Potenial energy lost = kinetic energy gained

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....*What else?*
- 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

Kinetik energy

$$KE = \frac{mv^2}{2}$$ (kJ)

Rate of kinetic energy:

$$\dot{KE} = \frac{\dot{m}v^2}{2}$$ (kJ/s) or (kW)

Internal energy

U (kJ)

is related to the degree of activity of molecules in a system

$$\rightarrow \Delta U = mC_\mathrm{V}\Delta T$$

Potential energy

$$PE = m \times g \times z$$ (kJ)

Rate of potential energy:

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

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)

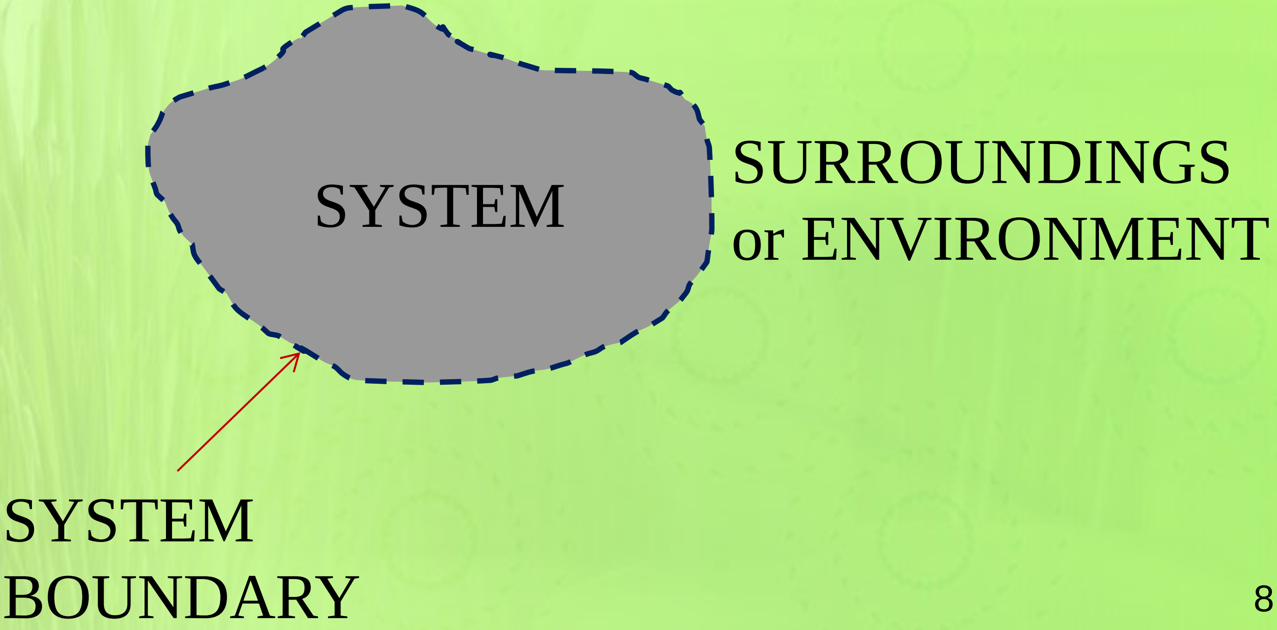
z : elevation from a referencepoint (m)

C_v : specificheat capacity at constant volume (kJ/kgK)

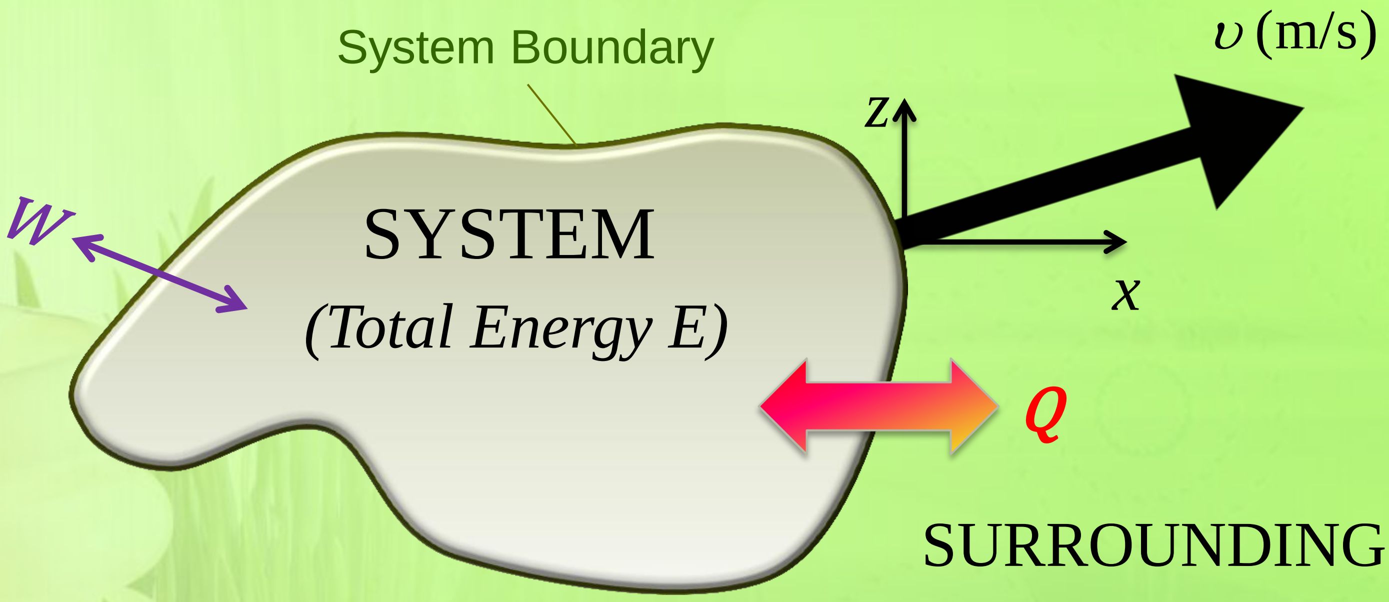
T : Temperature

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*.



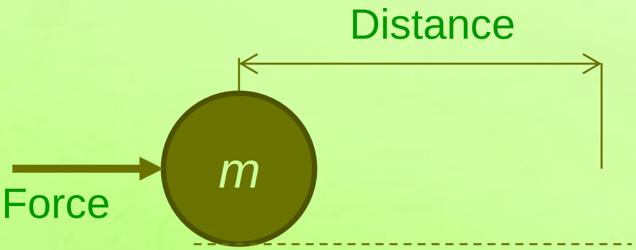
Thermodynamic System



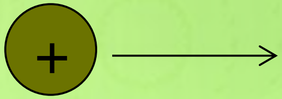
$$E = \text{the sum of all forms of energy}$$

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

Energy transfer by work

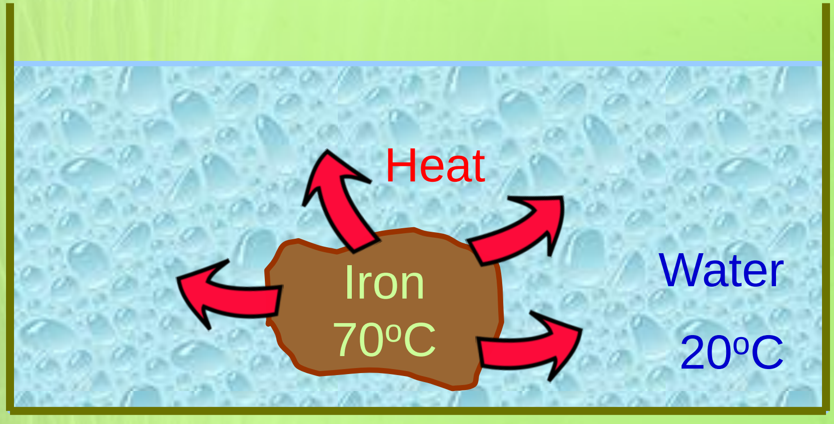


- The energy transfer associated with a force acting through a distance is called ***Work***
- Work = Force x Distance
- Unlike *heat* it is an energy interaction which is not caused by a temperature difference between a system and its surroundings
- A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions
- Moving a positive charge from one place to another requires work (i.e., electrical work)



Energy transfer by heat

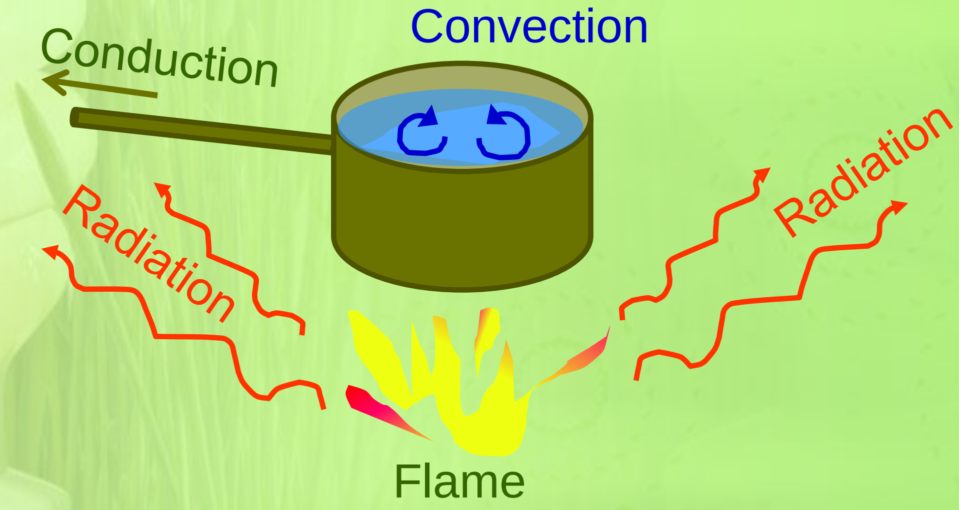
- When a thermodynamic system undergoes a process from one equilibrium state to another, a finite amount of heat energy is exchanged with the surroundings.
- *Heat* is a form of energy that can be transferred from one system to another as a result of temperature difference.
- The science that deals with the determination of the *rates* of such energy transfers is the *heat transfer*.



Temperature is the driving force of heat transfer.

Heat transfer mechanisms

- Heat can be transferred in three basic modes:
  - **conduction**
  - **convection**
  - **radiation**
- All modes of heat transfer require the existence of a temperature difference.



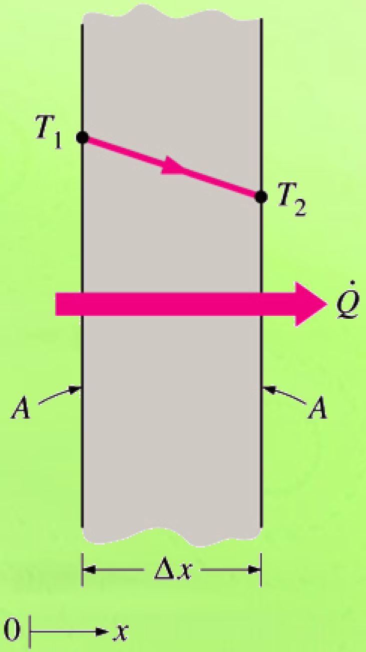
Conduction

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad \text{(W)}$$

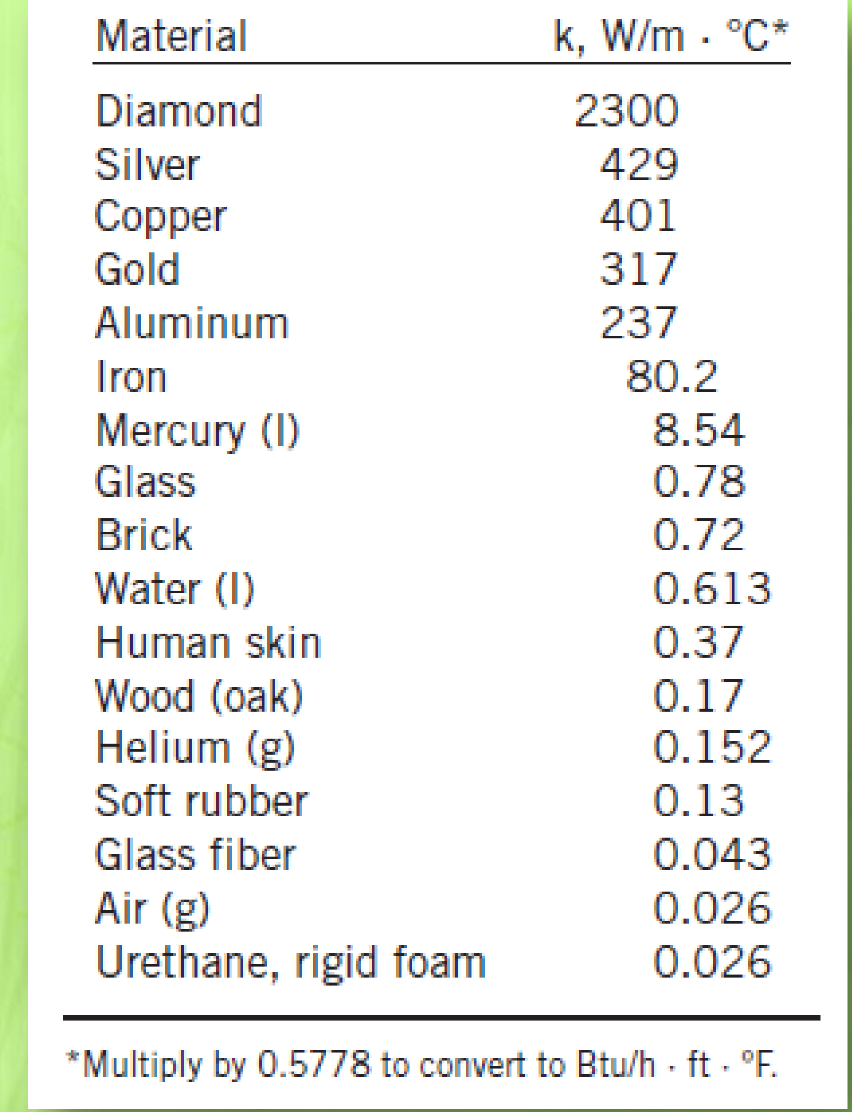
Thermal conductivity

The **thermal conductivity** of a material is a measure of the ability of the material to conduct heat.



Heat conduction through a large plane wall of thickness Δx and area A.

Thermal Conductivity of some materials at room temperature



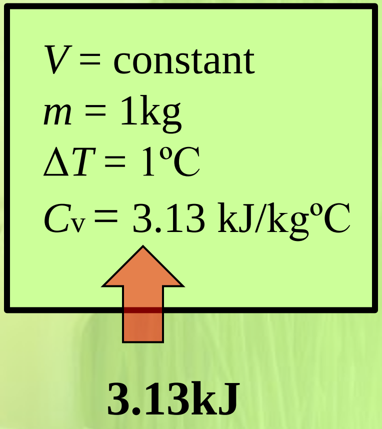
Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

*Multiply by 0.5778 to convert to Btu/h · ft · °F.

Heat capacity of a material

- **Specific heat capacity** of a substance is the energy required to raise the temperature of a unit of a substance by one degree.
- C_v = specific heat at constant volume
- C_p = specific heat at constant pressure.

Ex: Helium gas:



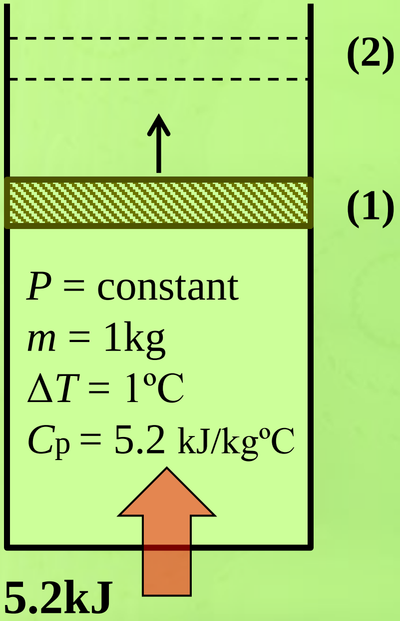
V = constant

m = 1kg

ΔT = 1ºC

C_v = 3.13 kJ/kgºC

3.13kJ



P = constant

m = 1kg

ΔT = 1ºC

C_p = 5.2 kJ/kgºC

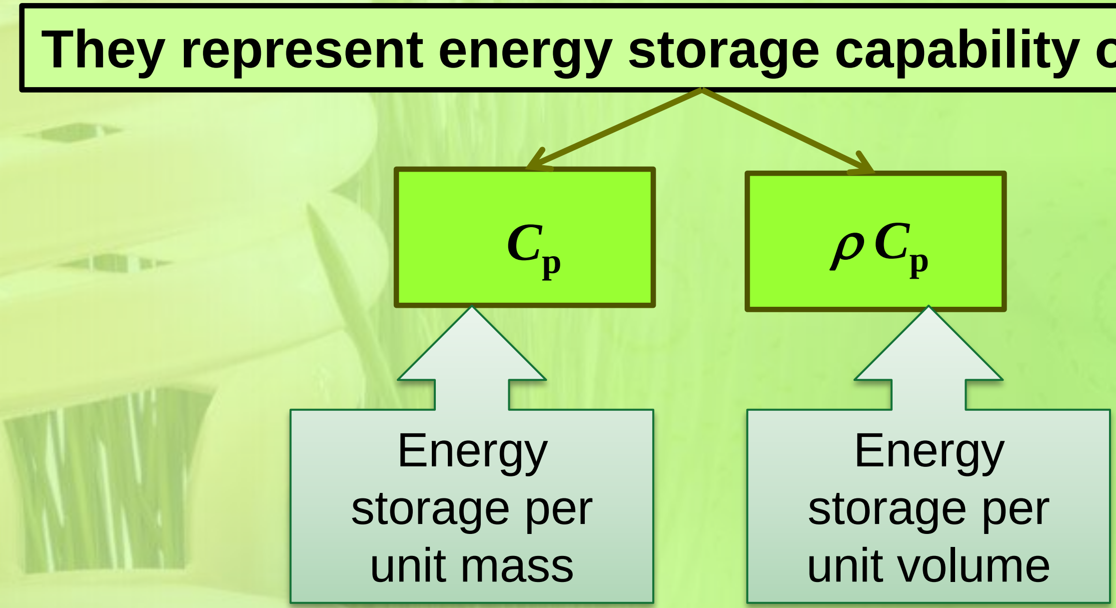
5.2kJ

$C_p > C_v$

Because at constant pressure, the energy required for expansion work must also be supplied to system.

Heat capacity of a material

- **Specific heat capacity (C_p)** of a substance is a measure of energy storage capability of a material in J/kg.°C.
- The product ρC_p is known as the **heat capacity** of a material. It represents energy storage capability of a material in J/m^3.°C



They represent energy storage capability of a material

C_p

ρC_p

Energy storage per unit mass

Energy storage per unit volume

Energy storage:

$$E_{st} = m \times C_p \times \Delta T$$

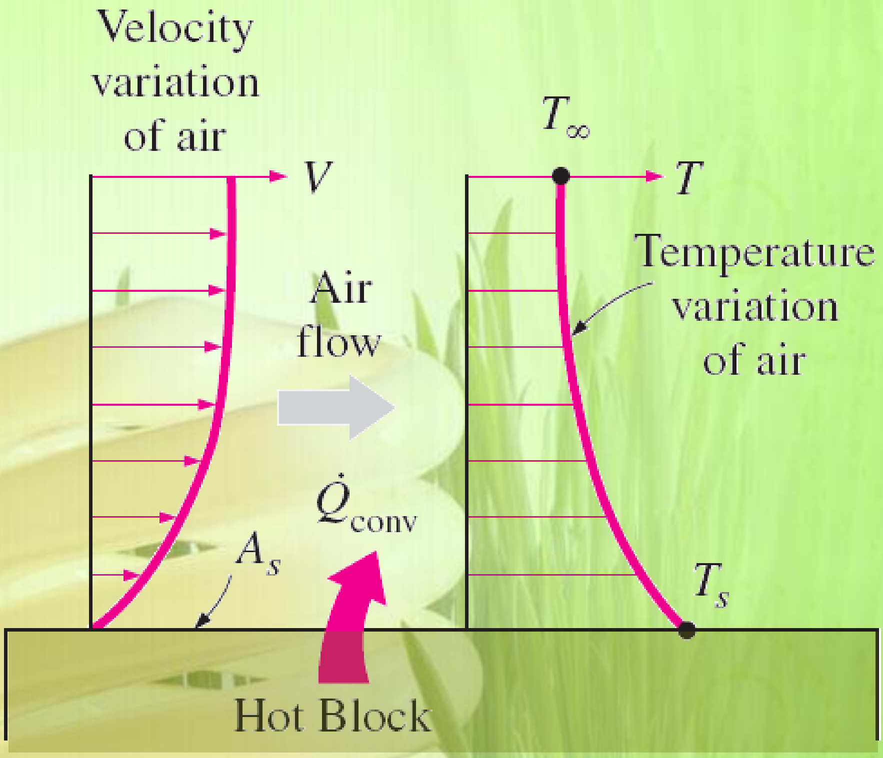
Thermal diffusivity of a material

- Represents how fast heat diffuses through a material
- Definition of thermal diffusivity:

$$\alpha = \frac{Heat\ conducted}{Heat\ stored} = \frac{k}{\rho C_p} \qquad (m^2/s)$$

- The larger the thermal diffusivity, the faster the propagation of heat into the medium
- A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat will be conducted

Convection



- Convection is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion.
- It involves the integrated effects of both conduction and fluid motion.
- The faster the fluid motion, the greater the convection heat transfer.
- If the fluid adjacent to a solid is not moving the heat transfer mode is pure conduction.

Convection

- Newton’s law of cooling:

$$Q_{conv} = h \times \underset{\substack{\nearrow \\ \text{Surface} \\ \text{area}}}{A_s} \times (\underset{\substack{\nwarrow \\ \text{Surface} \\ \text{temperature}}}{T_s} - T_\infty) \qquad \text{(W)}$$

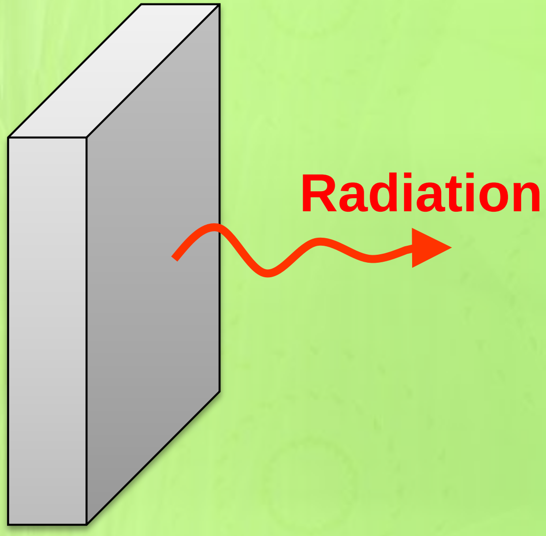
- h is the **convection heat transfer coefficient** (W/m2 ·°C or Btu/h ·ft2 ·°F). Some typical values are given as:

Type of convection	**h, W/m^2.^{o}C**
Free convection of gases	2 – 25
Free convection of lquids	10 – 1000
Forced convection of gases	25 – 250
Forced convection of liquids	50 – 20,000
Boiling and condensation	2500 – 100,000

Multiply by 0.176 to convert to Btu/h.ft^2.^{o}F

Radiation

- The heat energy emitted by objects in the form of electromagnetic waves or photons is known as radiation
- In heat transfer, radiation is driven by temperature of the bodies and it is independent of medium.
- In a solid, radiation originates from the surface.



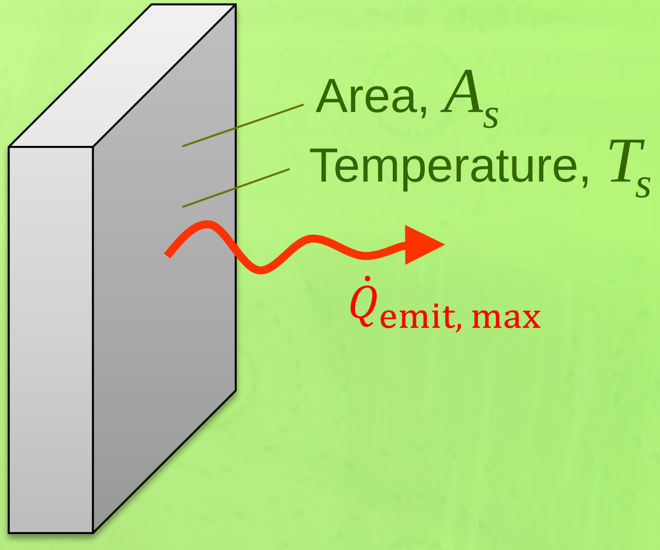
Radiation

- The maximum rate of radiation that can be emitted from a surface at an absolute temperature is known as **blackbody** radiation.
- Blackbody radiation is emitted by idealized surfaces.

Stefan–Boltzmann Law:

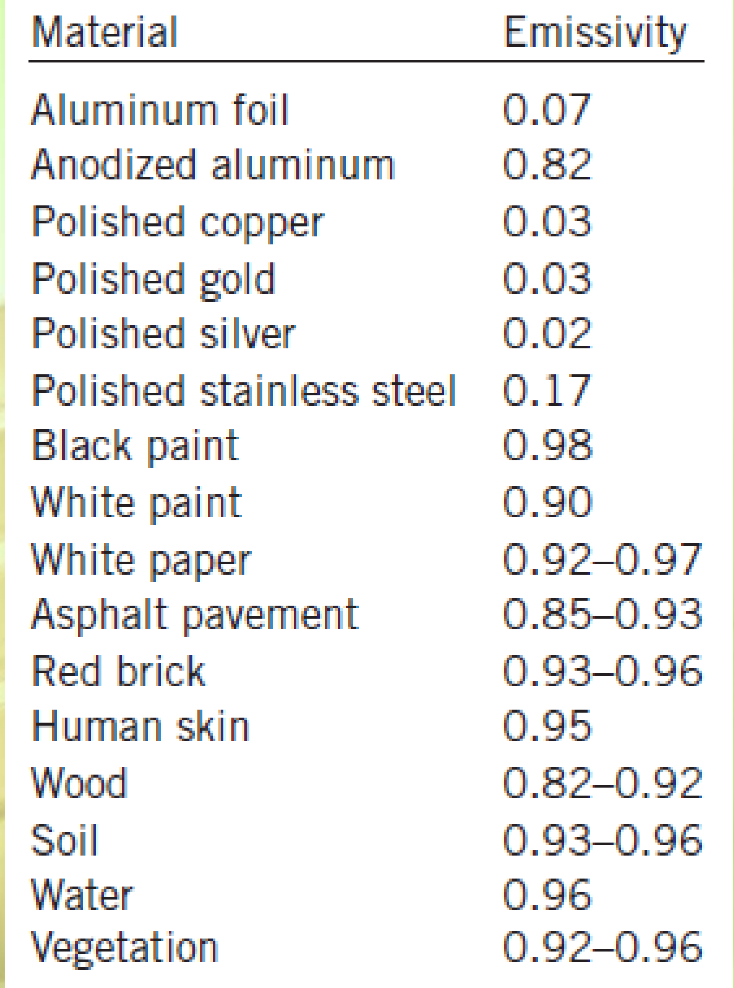
$$\dot{Q}_{\text{emit, max}} = \sigma A_s {T_s}^4$$

Stefan–Boltzmann constant
($\sigma = 5.67\times10^{8}$ W/m²·K⁴)



Radiation

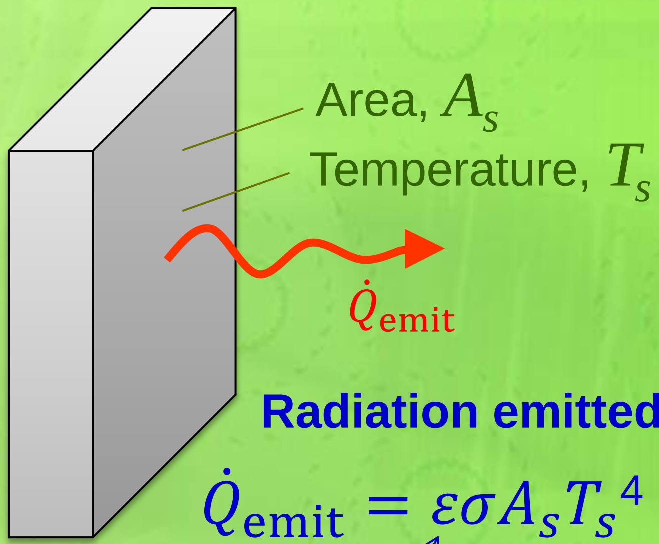
Emissivity of some materials at 300K



Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Emissivity

- Radiation emitted by real surfaces is less than that of emitted by a blackbody at the same temperature.
- Emissivity: $0 \geq \varepsilon \leq 1$, indicates how close a material is to blackbody



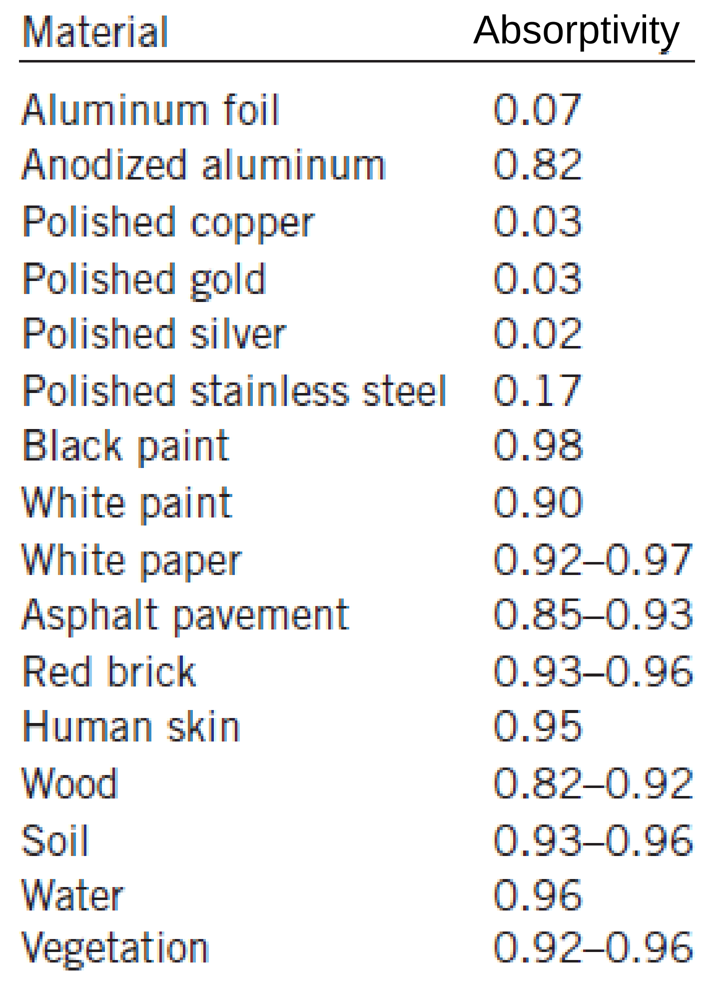
Radiation emitted:

$$\dot{Q}_{\mathrm{emit}} = \underset{\nearrow}{\varepsilon}\sigma A_s {T_s}^4$$

Emissivity of the surface

Radiation

Absorptivity of some materials at 300K



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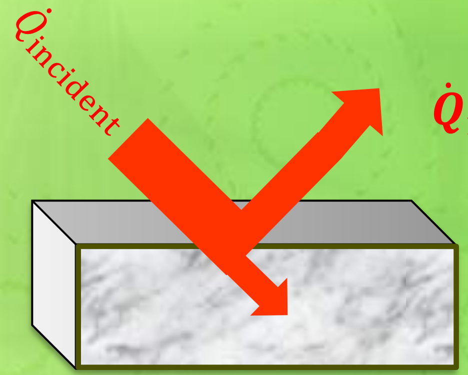
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Absorptivity

- It is the fraction of the radiation energy incident on a surface that is absorbed by a surface.
- According to the **Kirchhoff's law** the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.



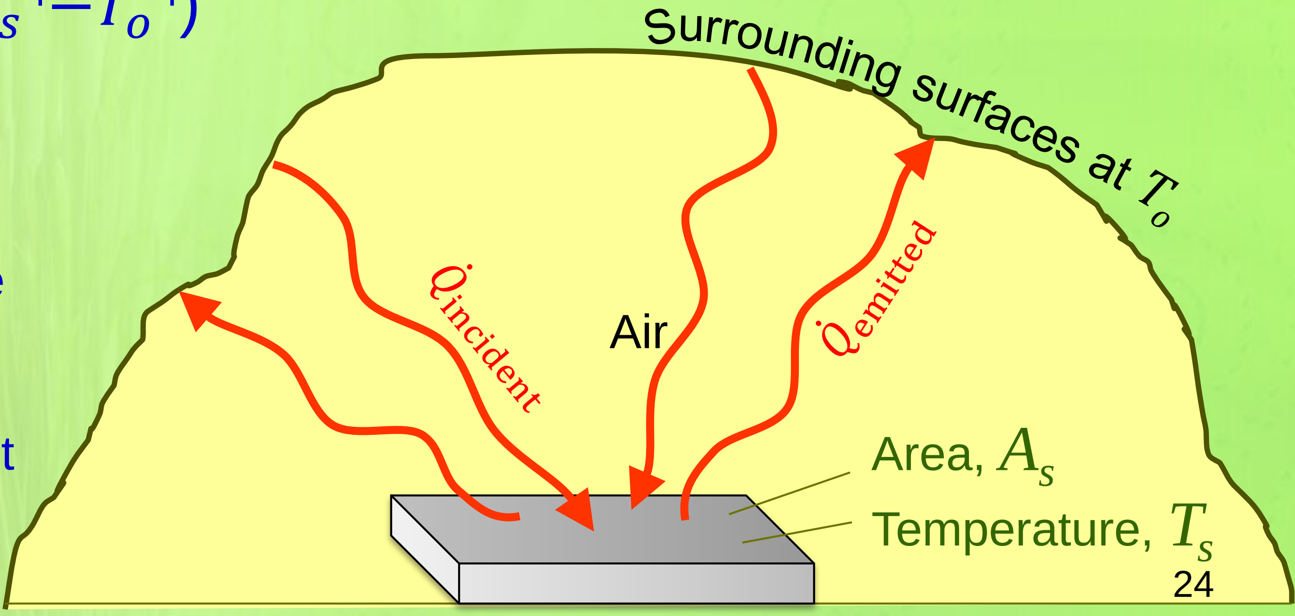
$$\dot{Q}_{\mathbf{ref}} = (\mathbf{1} - \boldsymbol{\alpha})\dot{Q}_{\boldsymbol{incident}}$$

$$\dot{Q}_{\text{abs}} = \alpha\dot{Q}_{\text{incident}}$$

Radiation

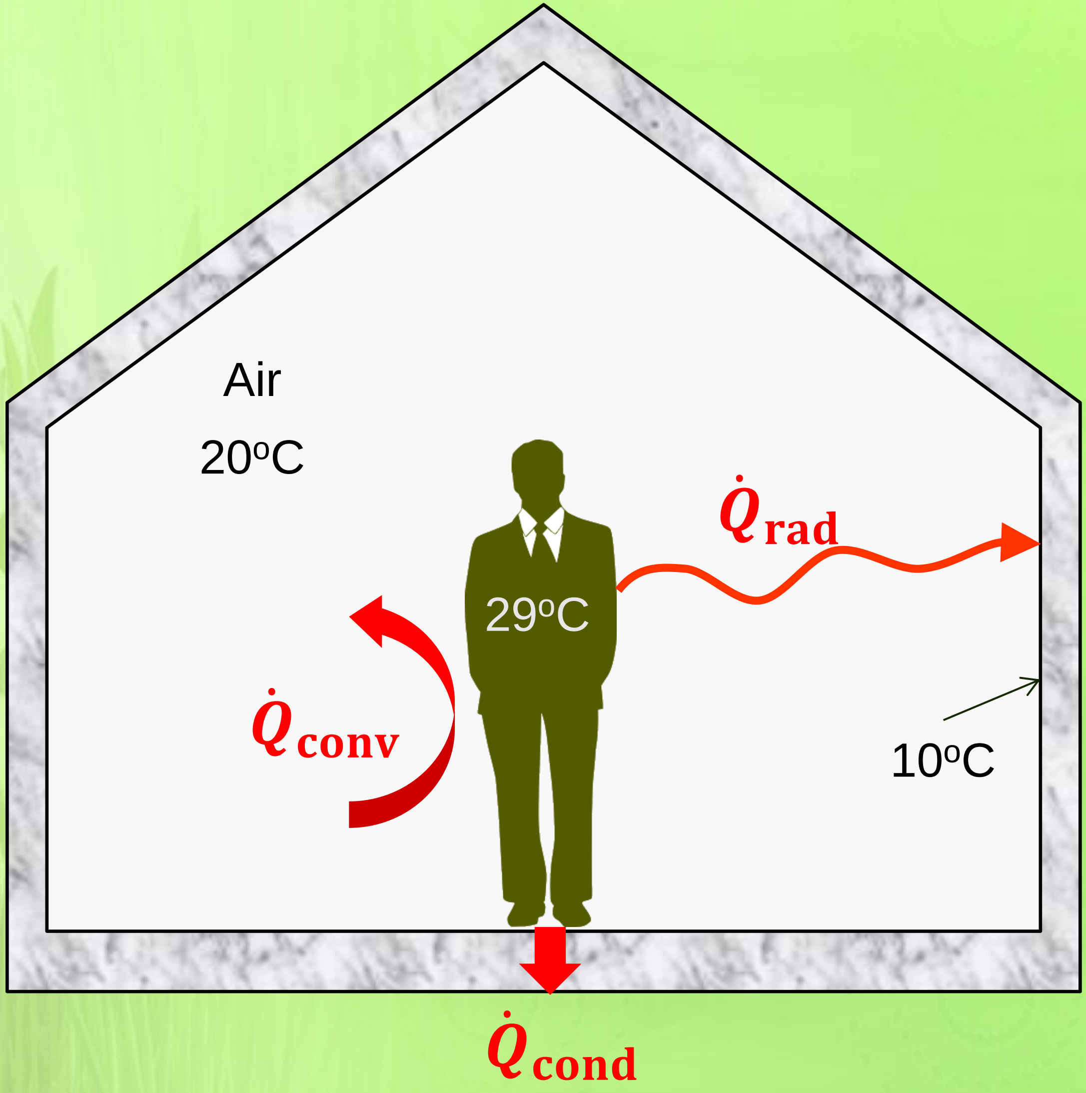
- Radiation heat transfer between a surface and a very large (black) surface surrounding it is shown below.
- Air in between does not intervene with radiation
- Net rate of radiation heat transfer is given by:

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s({T_s}^4 - {T_o}^4)$$



In this special case, the emissivity and the surface area of the surrounding surface do not have any effect on the net radiation heat transfer.

Effect of radiation on thermal comfort



Effect of radiation on thermal comfort

Example for winter

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

$$= \left(6\ \mathrm{W/m^2{}^\circ C}\right)\left(1.6\mathrm{m^2}\right)(29 - 20)^\circ\mathrm{C}$$

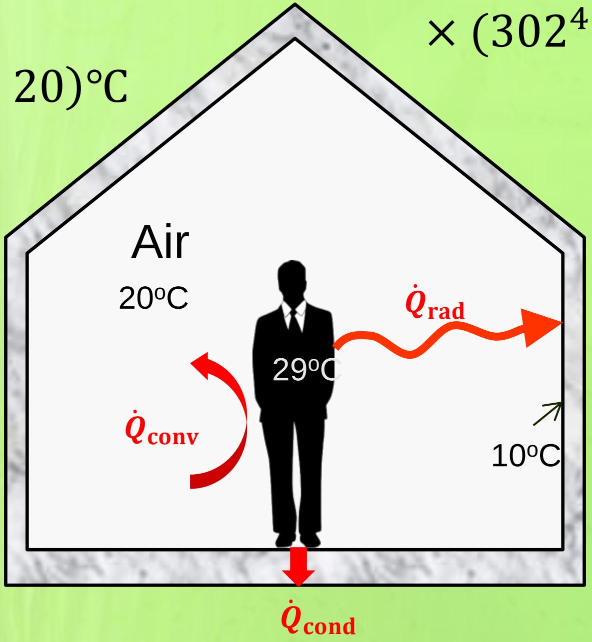
= 86.4 W

$$\dot{Q}_{rad} = \varepsilon\sigma A_s\left({T_s}^4 - {T_o}^4\right)$$

$$= (0.95)\left(5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}\right)\left(1.6\ \mathrm{m^2}\right)$$

$$\times\ (302^4 - 283^4)\mathrm{K^4}$$

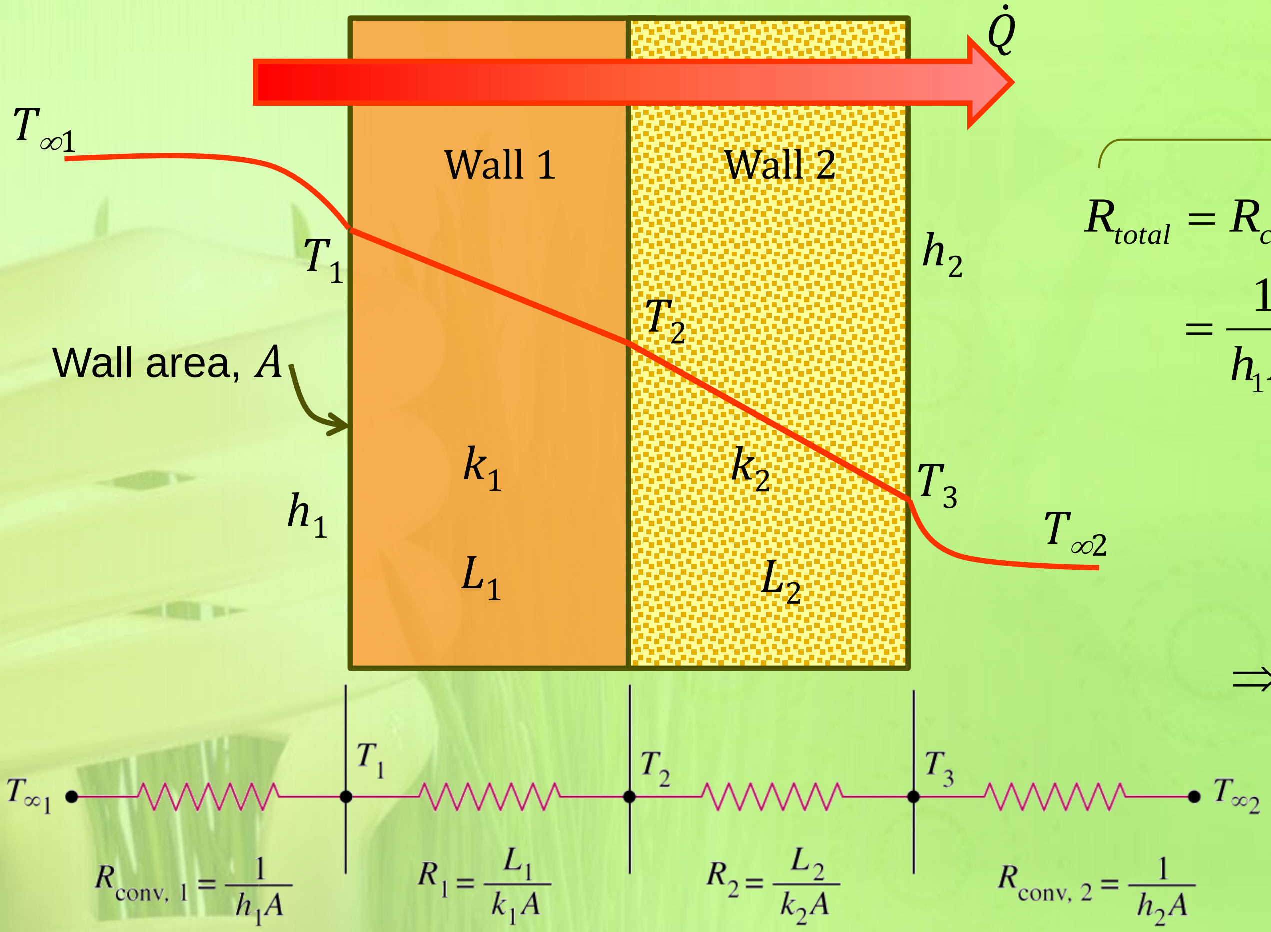
= **164 W**



Heat conduction through the feet is negligible

Heat loss through a wall

Rate of heat transfer through a wall made up of two different materials:



$$\dot{Q} = \frac{T_{\infty,1} - T_{\infty,2}}{R_{total}}$$

$$R_{total} = R_{conv,1} + R_{wall,1} + R_{wall,2} + R_{conv,2}$$

$$= \frac{1}{h_1 A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{1}{h_2 A}$$

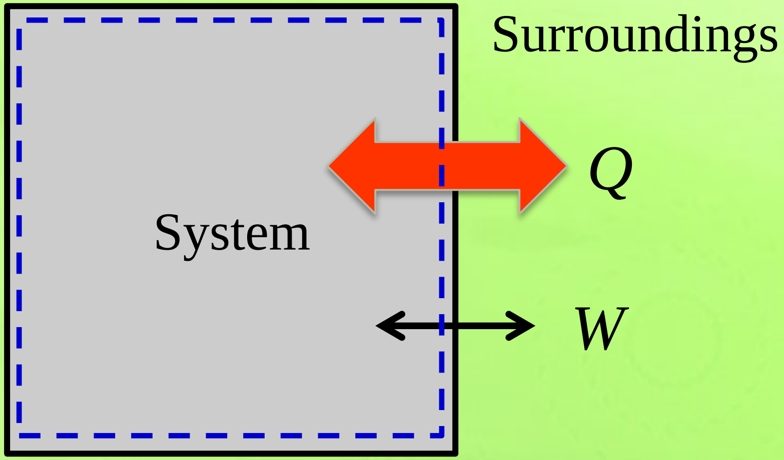
$$U = \frac{1}{A \times R_{total}}$$

$$\Rightarrow \dot{Q} = U \times A \times (T_{\infty 1} - T_{\infty 2})$$

Overall heat transfer coefficient
(also known as U-value)

Energy equation of closed systems in thermodynamics

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



$$\left\{\begin{array}{l}\text{Net energy transfer}\\ \text{to (or from) the system}\\ \text{as heat and work}\end{array}\right\} = \left\{\begin{array}{l}\text{Net increase (or decrease)}\\ \text{in the total energy}\\ \text{of the system}\end{array}\right\}$$

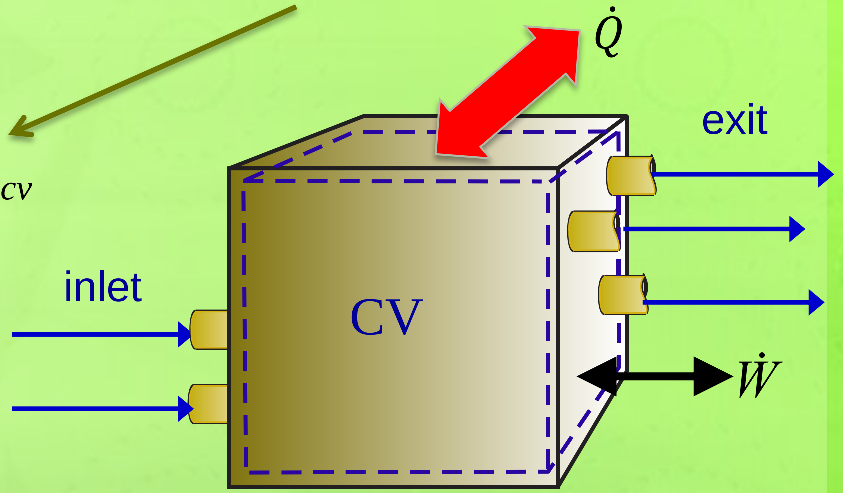
$$Q - W = \Delta E = \Delta U + \Delta KE + \Delta PE$$

$$= (U_2 - U_1) + m\frac{(\mathcal{V}_2)^2 - (\mathcal{V}_1)^2}{2} + mg(z_2 - z_1)$$

Steady flow energy equation (SFEE) of open systems in thermodynamics

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

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



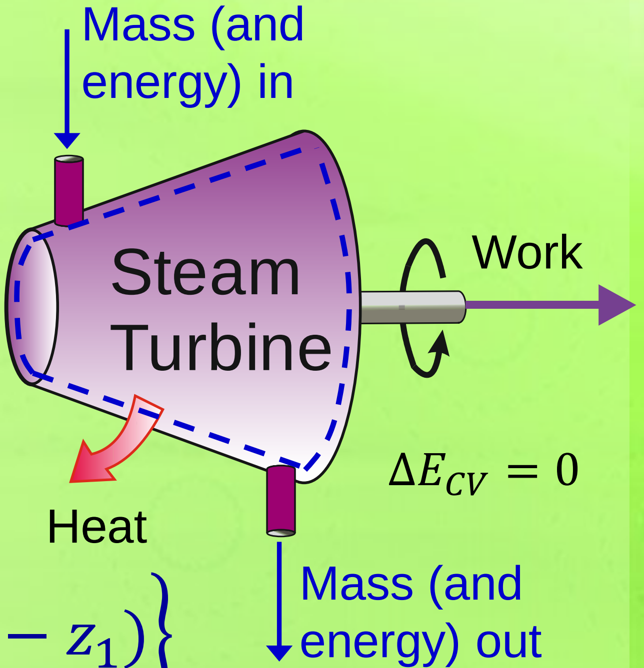
<u>Steady flow energy equation (SFEE)</u>

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

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

Where i = inlet, e = exit

Steady flow energy equation (SFEE) of open systems in thermodynamics



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:

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

Thermal comfort

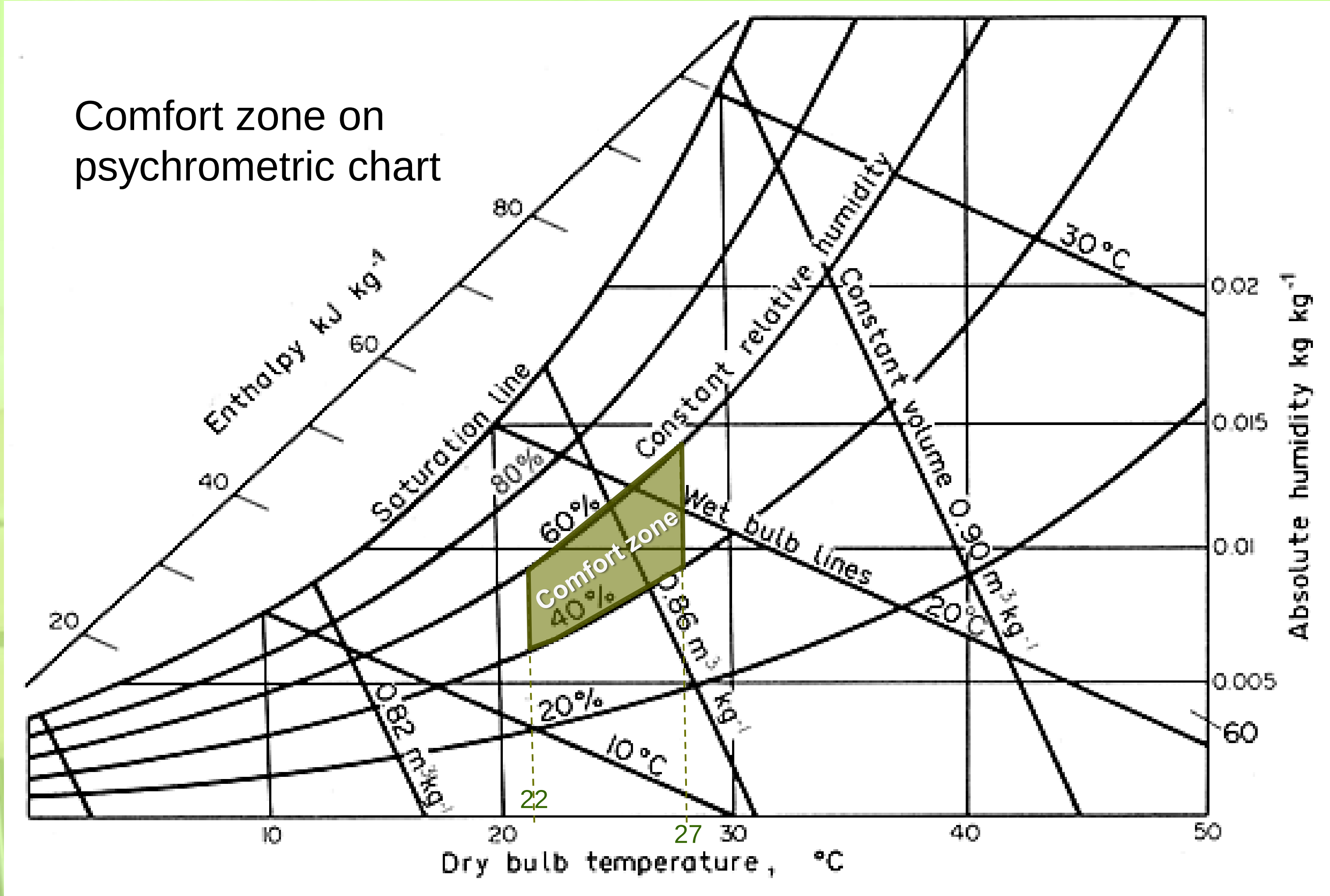
- Six factors affecting thermal comfort:
    - Air temperature
    - Mean radiant temperature (surface temperature)
    - Air velocity
    - Relative humidity
    - Clothing
    - Activity

Radiation to and from surfaces in a building

Thermal comfort is best between 40% – 60%

Heat is lost from the skin by **radiation**, **convection** and **evaporation**

Thermal comfort



Comfort zone on psychrometric chart

Fuels and combustion

- Fuels contain one or more of the following elements:
  - **carbon**
  - **hydrogen**
  - **sulphur**

- In reaction with oxygen during combustion these elements produce thermal energy

- The amount of thermal energy produced during combustion is called calorific value.

Fuels and combustion

Combustion of carbon

$$C + O_2 \rightarrow CO_2 + \text{energy}$$

- Carbon has an energy content of 32,793 kJ/kg

Combustion of hydrogen

$$H_2 + 2O_2 \rightarrow 2H_2O + \text{energy}$$

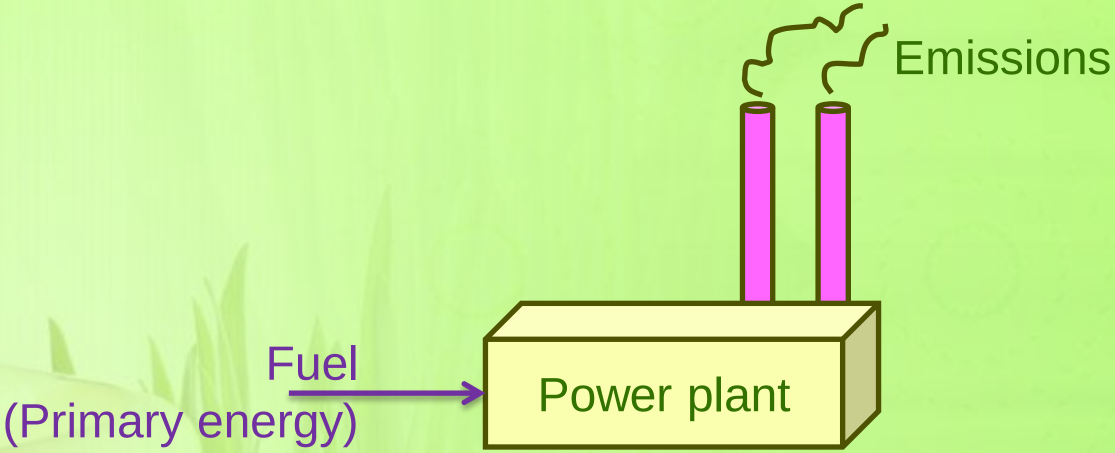
- Hydrogen has an energy content of 142,920 kJ/kg

Combustion of sulphur

$$S + O_2 \rightarrow SO_2 + \text{energy}$$

- Sulphur has an energy content of 9,300 kJ/kg

Environmental impacts of fossil fuels



Emissions

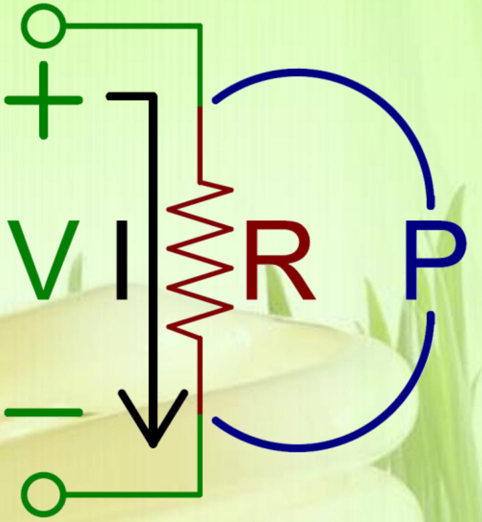
Fuel
(Primary energy)

Power plant

Fuel	Calorific value (MJ/kg)	CO_2 (kg/kg fuel)	CO_2/Energy (kg/kWh)	CO_2/Energy (kg/MJ)	SO_2 (kg/kg fuel)
Coal	26	2.361	0.309	0.091	0.018
Oil	42	3.153	0.263	0.075	0.040
Natural gas	55	2.750	0.179	0.055	0

Source: Tarik Al-Shemmeri. Energy Audits: A workbook for energy management in buildings (2011) Wiley-Blackwell.

Electric power



- **Electric power** is the rate at which **electrical energy** is transferred by an **electric** circuit.
- The SI unit of **electric energy** is joule or watt-hour
- The SI unit of **power** is watt, one joule per second.

Electrical energy: $W_{el} = V \times I \times t$

Voltage

Current

Electrical power: $\dot{W}_{el} = V \times I$

Units of electrical energy

- The watt (W) is a physical unit which is named after James Watt, the inventor of the steam engine.
- The basic unit of electrical energy is the watt-hour, or Wh.

Energy
1 Wh = 3600 Joules
1 kWh = 1000 Wh = 3600000 Joules = 3.6 MJ
1 MWh = 1000 kWh
1 GWh = 1000 MWh

Power
1 kW = 1000 W
1 MW = 1000 kW

How much power can fuels produce in a power plant?

One barrel of oil

- Can produce approximately 550 kWh

One kg of coal

- Can produce approximately 2 kWh

Generlally estimated from:

$$\dot{W}_{el} = \eta_{pp} \times \dot{m}_f \times HV$$

Word and numerical equivalent

- One J = 1 J.
- One thousand J = 1000 J = 10^3 J = **1 kJ**
- One million J= 1,000,000 J = 10^6 J = **1 MJ**
- One billion J = 1,000,000,000 = 10^9J = **1 GJ**

Energy conversion unit table (T-1)

1 kWh ……………………………………….. 3.6 MJ

1 m^3 LPG……………………………………25.56 GJ

1 kg #2 fuel oil ……………………………… 43.3 MJ

1 m^3 natural gas………………………………. 37 MJ

1 m^3 #2 fuel oil ……………………………39.85 GJ

1 litre LPG gas ……………………………... 7.1 kWh

1 kg LPG gas…………………………………12.68 kWh

1 litre #2 fuel oil……………………………11.07 kWh

1 kg #2 fuel oil……………………………..12.03 kWh

Energy unit conversion and railroad track method

- Since we have several different basic energy units and many different energy unit multipliers, energy managers must often convert from one set of energy units to another. There is a very systematic approach that can be applied to basic conversions, and also to more complex conversions and calculations.
- The principle of this unit conversion method is simply to carry out algebraically correct multiplications and divisions using correct units at each step, starting with the given piece of information and transforming it into the desired units using one or more conversion factors.

- For example, if we want to find the number (X) of Joules in 1000 cubic metres of natural gas, we can use this method as follows:

$$\text{X GJ of gas} = \begin{array}{l|l} 1000\ \text{m}^3 & 37{,}000\ \text{kJ} \\ \hline & \text{m}^3 \end{array} \longleftarrow \text{From Table T-1}$$

$$= \begin{array}{l|l} 1000\ \text{m}^3 & 37{,}000\ \text{kJ} \\ \hline \text{m}^3 & \end{array}$$

$$= \quad 1000 \times 37{,}000\ \text{kJ}$$

$$= \quad 37{,}000{,}000\ \text{kJ}$$

$$= \quad 37 \times 10^9\ \text{J}$$

$$= \quad 37\ \text{GJ}$$

- In the above calculation, cubic metres in the numerator and cubic metres in the denominator cancel out, and the remaining unit on the right side of the equation is J.
- Our goal was to end up with J as our desired unit on the right, and we made our unit conversions on the right side until we had the same unit as on the left side.

- If we ever perform one of these basic unit conversion calculations, and find that we have different units on the left and the right – we do not have the correct answer in terms of the desired units.
- This method is given the colloquial name Railroad Track Method, because the vertical separation lines remind us of railroad tracks.

Example Problem

Find the number (x) of kWh in 1000 cubic metres of natural gas.

From Table T-1

$$\text{X kWh of gas} = \begin{array}{c|c|c} 1000\ \text{m}^3 & 37{,}000\ \text{kJ} & 1\ \text{kWh} \\ \hline & \text{m}^3 & 3600\ \text{kJ} \end{array}$$

$$= \begin{array}{c|c|c} 1000\ \text{m}^3 & 37{,}000\ \text{kJ} & 1\ \text{kWh} \\ \hline \text{m}^3 & \text{kJ} & 3600 \end{array}$$

$$= \quad 1000 \times 37{,}000\ \text{kWh}/3600$$

$$= \quad 10{,}278\ \text{kWh}$$

Example Problem

How many J are in 10 kWh?

Solution

$$X\ \text{J} = \begin{array}{c|c} 10\ \text{kWh} & 3.6\ \text{MJ} \\ \hline & \text{kWh} \end{array}$$

$$= 36\ \text{MJ}$$

In this example, the two kWh units cancel out, leaving the remaining unit on the right side as J.

Example Problem

How many kWh are in 2500 MJ?

Solution:

$$X\ \text{kWh} = \begin{array}{c|c} 2500\ \text{MJ} & 3.6\ \text{kWh} \\ \hline & \text{MJ} \end{array}$$

$$= 694.44\ \ \text{kWh}$$

In this example, the two MJ units cancel out, leaving the remaining unit on the right side as kWh.

Example Problem

- A tank is filled with 100 litres of Number 2 fuel oil. How many **GJ** of energy is contained in the tank of oil?

Solution

- From Table T-1, there are 39 MJ per litre of oil.

$$X\ \text{GJ} = \begin{array}{c|c|c} 100\ \text{L} & 39\ \text{MJ} & 1\ \text{GJ} \\ \hline & 1\ \text{L} & 1000\ \text{MJ} \end{array}$$

$$= 3.9\ \text{GJ}$$

- In this example, the two litre units cancel out, and the two MJ units cancel out, leaving the remaining unit on the right side as GJ, our desired unit.

Example Problem

- A tank is filled with 100 litres of Number 2 fuel oil. How many **kWh** of energy is contained in the tank of oil?

Solution

- From Table T-1, there are 39 MJ per litre of oil.

$$X\ \text{kWh} = \begin{array}{c|c|c} 100\ \text{L} & 39\ \text{MJ} & 1\ \text{kWh} \\ \hline & 1\ \text{L} & 3.6\ \text{MJ} \end{array}$$

$$= 1083.3\ \text{kWh}$$

- In this example, the two litre units cancel out, and the two MJ units cancel out, leaving the remaining unit on the right side as kWh, our desired unit.

Energy audit: *searching for energy saving opportunities*

- It is a work conducted to analyze the energy performance of a facility, system or a process.
- Its objective is to bring out the energy efficiency opportunities and put them into order of priority.
- Cost-effect measures are proposed to lower the energy use of the facility.
- It is the first step of effective energy management.
- Energy audit will be studied in more detail in Chapter 4.

EU Directives and standards on energy audit

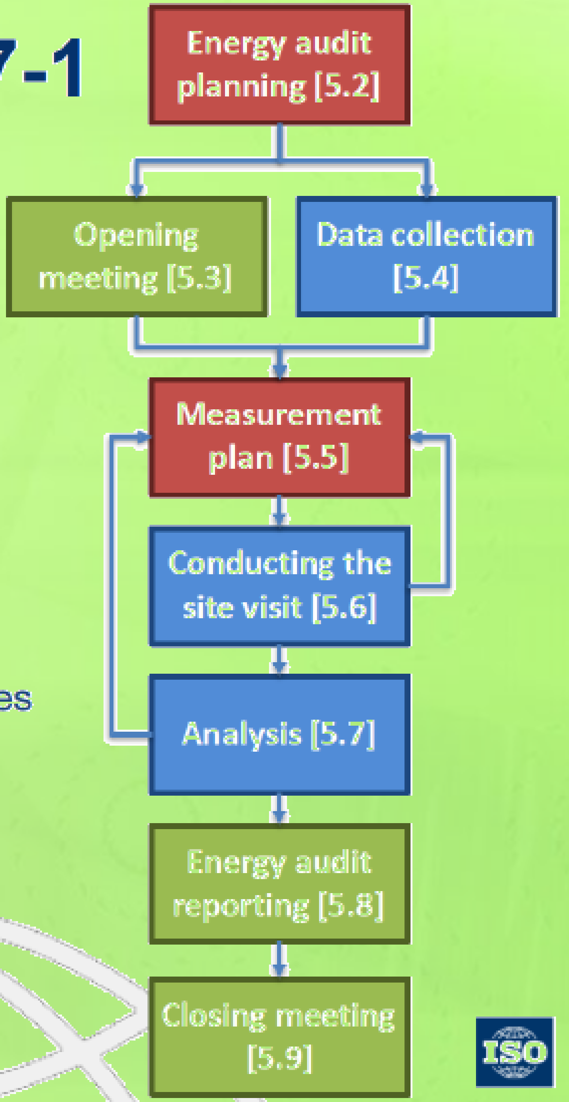
ISO 50002 and EN 16247-1

1. General
2. Energy audit planning
3. Opening meeting
4. Data collection
5. Measurement plan
6. Conducting the site visit
    - 5.6.1 Management of field work
    - 5.6.2 Site visits

5.7 Analysis
- 5.7.1 General
- 5.7.2 Analysis of current energy performance
- 5.7.3 Identification of improvement opportunities
- 5.7.4 Evaluation of improvement opportunities

5.8 Energy audit reporting
- 5.8.1 General
- 5.8.2 Energy audit report content

5.9 Closing meeting



Source: Energy Management System Training, Nicosia, June 2019