Exergy

Dr. Md. Zahurul Haq, *Ph.D., CEA, FBSME, FIEB*

Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh

http://zahurul.buet.ac.bd/

ME 203: Engineering Thermodynamics
`http://zahurul.buet.ac.bd/ME203/`

Energy: Quantity & Quality

- Energy has both quantity and quality.
- *Quality of energy* is its potential to produce useful work.
- First Law of Thermodynamics:
  energy is conserved in all (non-nuclear) processes.
- Second Law of Thermodynamics:
  the quality of energy is reduced in all real processes.

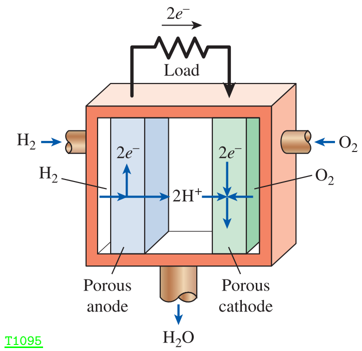
⇒ During transformation and transfer, energy is both conserved and degraded.

- Exergy provides a direct relationship between the thermodynamic state of a system and its capability to do useful work.

Datum Condition & Useful Work

Standard atmosphere:
$P_0 = 101.325$ kPa, $T_0 = 298.15$ K

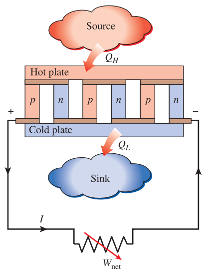
Species	RH = 60%	RH=100%
N_2	0.7662	0.7564
O_2	0.2055	0.2029
CO_2	0.0003	0.0003
H_2O	0.0188	0.0313
Other	0.0092	0.0091



T1095

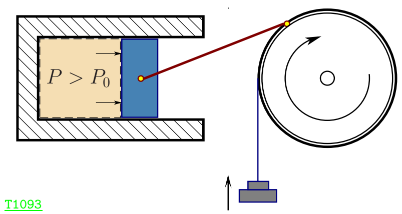
When the pressure, temperature, composition, velocity, or elevation of a system is different from the environment, there is an opportunity to develop work.

T1097

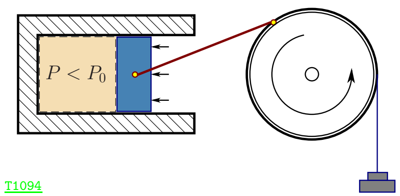


T1096

Useful work could be produced by utilizing temperature deviation from the environment.



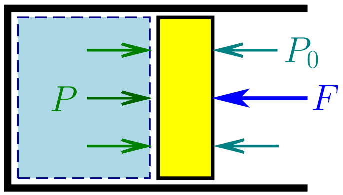
T1093



T1094

Energy contains exergy when – and only when – that energy is not in equilibrium with its environment

Useful Work (W_u) & Datum State (T_0, P_0)



T345

Datum state

- P_0 = 101.325 kPa
- T_0 = 298.15 K

- If $P \approx P_0 \Rightarrow W = \int_1^2 PdV = P_0 \Delta V \neq 0$;
  $\longrightarrow$But useful work, $W_u = 0$.
- $\delta W_u = \vec{F}.d\vec{x} = (P - P_0)A_s dx = (P - P_0)dV = \delta W - P_0 dV$

$\Rightarrow$ $$\boxed{\delta W_u = \delta W - P_0 dV = \delta W - \delta W_{surr}}$$

- As a closed system expands, some work needs to be done to push the atmospheric air out of the way (and, vice versa) $\rightsquigarrow W_{surr}$.

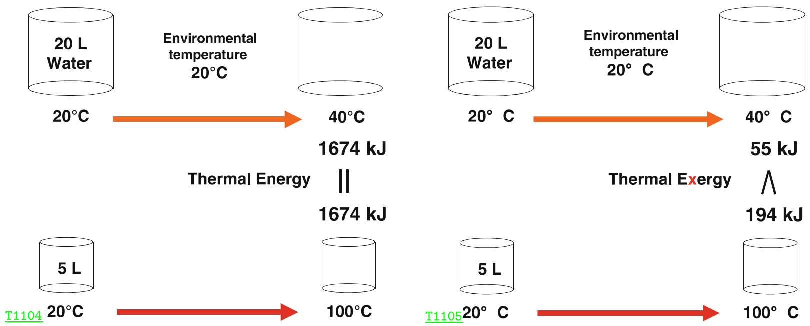
$\Rightarrow$ *Surrounding work (W_{surr}) is not recoverable & can't be utilized.*

Dead State & Exergy (eX)

- A system in a dead state is in thermal & mechanical equilibrium with environment at T_0 & P_0 (T_0 = 298.15 K, P_0 = 101.325 kPa).
- Exergy of a system in a closed system in a given state is the maximum useful work output that may be obtained from a system-environment combination as the system proceeds from a specified equilibrium state to the dead state, while exchanging heat solely with the environment.
- Exergy, $eX \equiv \frac{Ex}{m}$ is the sum of thermo-mechanical, KE, PE, chemical exergies:

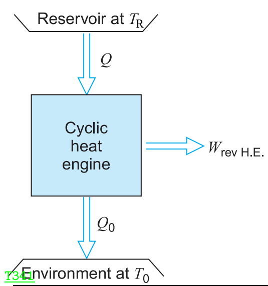
$$eX = eX_{TM} + eX_{KE} + eX_{PE} + eX_{CH} + \cdots$$

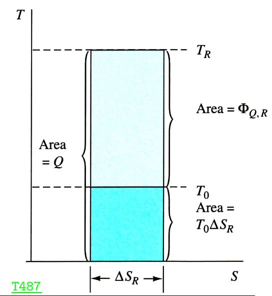
- Exergy is a function of both the state of the system & the local environment. Once the environmental conditions are standardized, exergy is treated as a property of the system alone.
- At dead state, exergy of the system is zero.



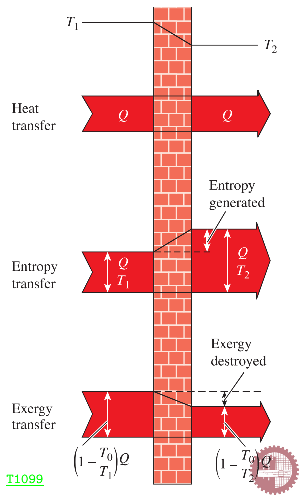
T1104 T1105

Exergy of Heat (eX_Q)





T341 T487

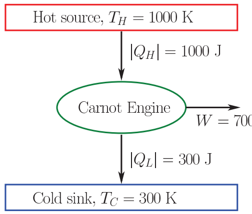


T1099

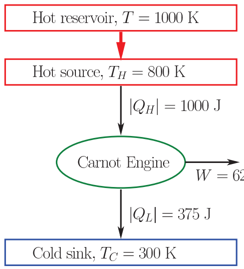
$$\Phi_Q \equiv W_{rev,HE} = Q\left(1 - \frac{T_0}{T_R}\right)$$

$$\Phi_Q = \sum_{j=0}^{n} Q_j \left(1 - \frac{T_0}{T_j}\right)$$

$$I_Q = \Phi_{Q,1} - \Phi_{Q,2} = T_0 Q\left[\frac{1}{T_2} - \frac{1}{T_1}\right] = T_0 \sigma_Q$$



T384



T385

- $\eta_{carnot} = 1 - 300/1000 = 0.7$
- $|W| = 1000(0.7) = 700$ J
- $|Q_L| = 1000 - 700 = 300$ J
- $\eta_{carnot} = 1 - 300/800 = 0.625$
- $|W| = 1000(0.625) = 625$ J
- $|Q_L| = 1000 - 625 = 375$ J

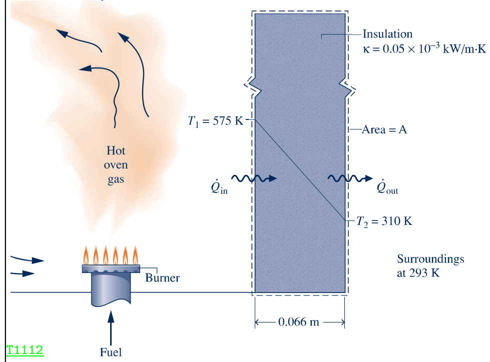
⇒ Exergy destruction for heat transfer from 1000 K to 800 K, Ex_Q

⇒ $Ex_Q = 1000(300)(1/800 - 1/1000) = 75$ J

⇒ Reversible work loss = 700 J - 625 J = 75 J.

Heat Conduction Through Wall

Moran, Ex. 7-3 ▷



T1112

- $\dot{q} = -k\left[\frac{T_2 - T_1}{L}\right] = 0.2\ \frac{kW}{m^2}$
- $\dot{\phi}_{Q,in} = q\left[1 - \frac{T_0}{T_1}\right] = 0.1\ \frac{kW}{m^2}$
- $\dot{\phi}_{Q,out} = q\left[1 - \frac{T_0}{T_2}\right] = 0.01\ \frac{kW}{m^2}$
- $I_Q = \dot{\phi}_{Q,in} - \dot{\phi}_{Q,out} = 0.09\ \frac{kW}{m^2}$

Equations: CM & CV Systems

CM System:

- $Q - W = \Delta U$
- $W_u = W - P_0 \Delta V = W - W_0$
- $\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $\Phi_Q = \sum_{j=1}^{n} Q_j \left(1 - \frac{T_0}{T_j}\right)$
- $\Delta\Phi = \Phi_Q - W_u - I_{cm}$

SSSF CV System:

- $Q - W_{sf} = m(\Delta h + \Delta pe + \Delta he) = m\Delta h$
- $W_u = W_{sf} - P_0 \cancel{\Delta V}^{0} = W_{sf}$
- $\psi = (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz$
- $\Phi_Q = \sum_{j=1}^{n} Q_j \left(1 - \frac{T_0}{T_j}\right)$
- $\Delta(m\psi) = \sum_e \dot{m}_e \psi_e - \sum_i \dot{m}_i \psi_i = \dot{\Phi}_Q - \dot{W}_u - \dot{I}_{cv}$

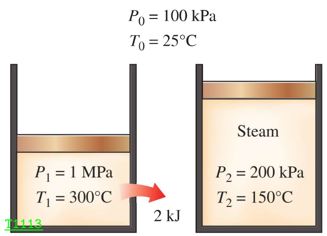
Example: Exergy of Air

- $\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $u - u_0 = c_v(T - T_0)$
- $v = \frac{RT}{P}$
- $s - s_0 = c_V \ln\left(\frac{T}{T_0}\right) + R\ln\left(\frac{v}{v_0}\right) = c_P \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right)$
- Environment: $T_0 = 298.15$ K, $P_0 = 101.325$ kPa.
  - ▷ Air at 298.15 K & 101.325 kPa: $\phi = 0$ kJ/kg
  - ▷ Air at 298.15 K & 50 kPa: $\phi = 27.4$ kJ/kg
  - ▷ Air at 298.15 K & 200 kPa: $\phi = 16.0$ kJ/kg
  - ▷ Air at 200 K & 101.325 kPa: $\phi = 20.8$ kJ/kg
  - ▷ Air at 400 K & 101.325 kPa: $\phi = 14.4$ kJ/kg

When the pressure, temperature, composition, velocity, or elevation of a system is different from the environment, there is an opportunity to develop work.

CM System: Expansion of Steam inside Cylinder

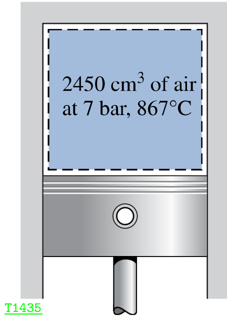
Cengel, Ex. 8-11 ▷ Piston-cylinder assembly contains 0.05 kg steam.



- $Q - W = m(\Delta u + \Delta KE + \Delta PE) \simeq m\Delta u$
- $\phi \equiv (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $W_u = W - W_0 = 8.826 - 3.509 = 5.317$ kJ
- $\phi_Q = 0$: Heat loss to T_0
- $\Delta\phi = -9.648$ kJ
- $I_{CM} = \phi_Q - W_u - \Delta\phi = 4.331$ kJ
- $\epsilon = \frac{W_u}{-\Delta\phi} = 0.551$

Evaluating the Exergy of Exhaust Gas

Moran Ex. 7.1 ▷ A cylinder of an internal combustion engine contains 2450 cm^3 of gaseous combustion products at a pressure of 7 bar and a temperature of 867°C just before the exhaust valve opens. Determine the specific exergy of the gas, in kJ/kg. Assume, the combustion products as air as ideal gas.

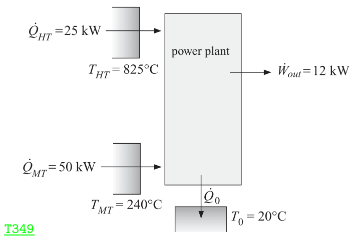


- $T_0 = 300$ K, $P_0 = 1.0$ bar
- $\phi \equiv (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$
- $u - u_0 = c_v(T - T_0) = 600$ kJ/kg
- $P_0(v - v_0) = R(\frac{P_0 T}{P} - T_0) = 39.36$ kJ/kg
- $s - s_0 = c_p \ln(T/T_0) - R\ln(P/P_0) = 0.7870$ kJ/kg
- $\phi = 324.54$ kJ/kg

Second Law Efficiency (η_{II}) or Effectiveness (ϵ)

- A performance parameter based on the exergy concept is know as Second Law Efficiency (η_{II}) or as Second Law Effectiveness (ϵ).
- A first-law efficiency gages how well the energy is used when compared against an ideal process, whereas an effectiveness indicates how well exergy is utilized.

$$\eta_{II} \equiv \epsilon \equiv \frac{\text{useful exergy out}}{\text{exergy in}} = 1 - \frac{\text{exergy destruction}}{\text{exergy in}}$$



- $\eta_I = \frac{W_{out}}{Q_{HT} + Q_{MT}} = \frac{12}{25+50} = 16\%$
- $Ex_{HT} = 25\left(1 - \frac{293}{1098}\right) = 18.33$
- $Ex_{MT} = 50\left(1 - \frac{293}{513}\right) = 21.44$
- $\eta_{II} = \frac{W_{out}}{Ex_{HT} + Ex_{MT}} = 30.2\%$

Adiabatic Compression & Pumping

CM process:

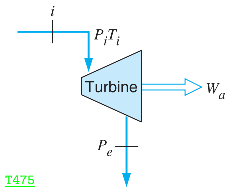
- $\Delta\Phi = \Phi_Q - W_u - I_{cm}$
- $W_u = W_{act} + P_0\Delta V$
- $\boxed{\epsilon \equiv \frac{\Delta\Phi}{W_{act}}}$

CV process:

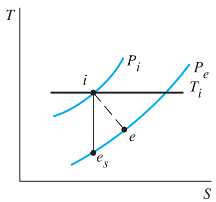
- $\Delta\Psi = \Phi_Q - W_u - I_{cv}$
- $W_u = W_{act}$
- $\boxed{\epsilon \equiv \frac{\Delta\Psi}{W_{act}}}$

- Effectiveness (ϵ) is defined as the increase in the specific availability of the fluid per unit of actual work input.
- First law efficiency, $\eta \equiv \frac{W_s}{W_{act}}$.

Steam/Gas Turbine, Throttling & Nozzle



T475



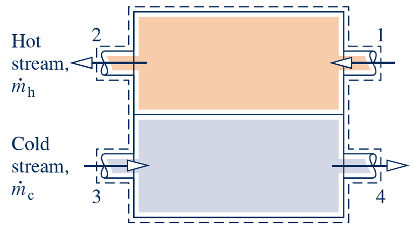
Turbines:

- $\eta = \frac{w_a}{\Delta h}$
- $\Delta\psi = \phi_Q - w_u - i_{cv}$
- $\boxed{\epsilon = \frac{w_a}{\Delta\psi}}$

- Throttling:
- $0 = \cancel{q}^0 - \cancel{w}^0 + h_i - h_e - \cancel{\Delta ke}^0$
- $\Delta\psi = \cancel{\phi_Q}^0 - \cancel{w_u}^0 - I_{cv}$
- $\boxed{\epsilon = \frac{\psi_e}{\psi_i}}$

- Nozzle:
- $\cancel{q}^0 + \cancel{w}^0 = h_e - h_i + \Delta ke$
- $\eta = \frac{\Delta ke_a}{\Delta ke_s}$
- $\Delta\psi = \cancel{\Phi_Q}^0 + \cancel{w_u}^0 - I_{cv}$
- $\boxed{\epsilon = \frac{\Psi_e}{\Psi_i}}$

Heat Exchange without Mixing



T476

- $w = 0,\ q = 0,\ \Delta ke = 0,\ \Delta pe = 0$
- SSSF Energy: $0 = 0 - 0 + \sum_i (mh)_i - \sum_e (mh)_e$

$\Rightarrow m_1 h_1 + m_3 h_3 = m_1 h_2 + m_4 h_4 \rightarrow \boxed{m_c(h_4 - h_3) = -m_h(h_2 - h_1)}$

- Exergy balance:

$\Delta(m\Psi) = \cancel{\Phi_Q}^0 - \cancel{W}^0 - I\,cv \rightarrow m_c(\psi_4 - \psi_3) + m_h(\psi_2 - \psi_1) = -I_{cv}$

$\Rightarrow$ $\boxed{\epsilon \equiv \frac{m_c(\psi_4 - \psi_3)}{-m_h(\psi_2 - \psi_1)} \quad \text{or} \quad \epsilon \equiv \frac{m_c\psi_4 + m_h\psi_2}{m_c\psi_3 + m_h\psi_1}}$

- The first form of ϵ for heat exchanger is usually preferred.

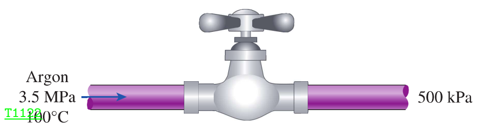
SSSF Compressor

Holman, Ex. 5.10: ▷ A steady-flow compressor is used to compress air from 1 bar, 25°C to 8 bar in an adiabatic process. The first-law efficiency, η_I, of the process is 87%. Calculate the irreversibility and η_{II} of the process if $T_0 = 293$ K.

- $\Psi \equiv (h - h_0) - T_0(s - s_0) + \frac{\mathbb{V}^2}{2} + gz \cong (h - h_0) - T_0(s - s_0)$
- $w_a = h_1 - h_2 = -c_P(T_2 - T_1)\ :\ w_s = h_1 - h_{2s} = -c_P(T_{2s} - T_1)$
- $\eta_I = \frac{w_s}{w_a} = 0.87$
- $T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = 540 \text{ K} \rightarrow T_{2a} = \frac{W_a}{C_p} + T_1 = 571 \text{ K}$
- $w_a = -279.0$ kJ/kg
- $w_{min} = -\Delta\Psi = -[(h_{2a} - h_1) - T_0(s_{2a} - s_1)] = -259.8$ kJ/kg
- $i_{sf} = T_0(s_{2a} - s_1) = 19.2$ kJ/kg
- $\eta_{II} = \frac{\Delta\Psi}{w_a} = 0.931$ ◀

Throttling Process

Cengel, P. 8-130 ▷ Argon gas expands from 3.5 MPa and 100°C to 500 kPa in an adiabatic expansion valve. For environment conditions of 100 kPa and 25°C, determine (a) the exergy of argon at the inlet, (b) the exergy destruction during the process, and (c) the second-law efficiency.

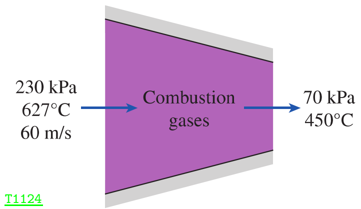


T1130

- $\psi_1 = 223.8$ kJ
- $\psi_2 = 103.3$ kJ
- $I_{cv} = -\Delta\psi = 120.5$ kJ
- $\epsilon = \frac{\psi_2}{\psi_1} = 0.461$

Nozzle

Cengel, P. 8-71 ▷ Hot combustion gases enter the nozzle of a turbojet engine. Assuming the nozzle to be adiabatic and the surroundings to be at 20°C, determine (a) the exit velocity and (b) the decrease in the exergy of the gases. Take air properties for the combustion gases.

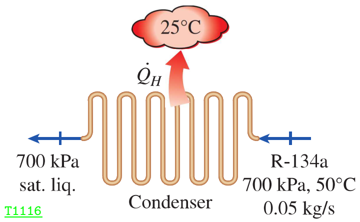


T1124

- $V_2 = \sqrt{V_1^2 - \Delta KE} = 627$ m/s
- $\psi_1 = 368.9$ kJ
- $\psi_2 = 339.4$ kJ
- $I_{cv} - \Delta\psi = 29.5$ kJ
- $\epsilon = \frac{\psi_2}{\psi_1} = 0.92$

Air Cooled Condenser

Cengel, P. 8-63 ▷ Determine (a) the rate of heat rejected in the condenser, (b) the COP of this refrigeration cycle if the cooling load at these conditions is 6 kW, and (c) the rate of exergy destruction in the condenser.

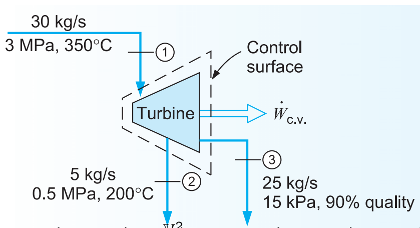


T1116

- $Q_L = 6$ kW
- $Q_H = \dot{m}(h_2 - h_1) = 9.98$ kW
- $COP = \frac{Q_L}{W_{in}} = \frac{Q_L}{Q_H - Q_L} = 1.5$
- $I_{cv} = -\Delta\psi = 0.0998$ kW
- $\epsilon = \frac{\psi_e}{\psi_i} = 0.955$

SSSF Turbine

Borgnakke, Ex. 8.5: ▷

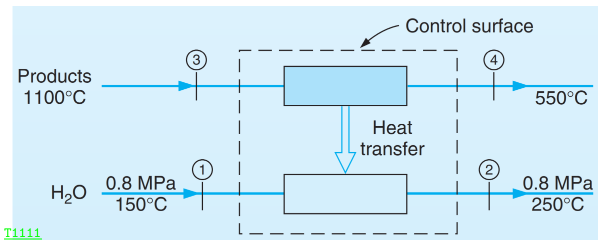


T351

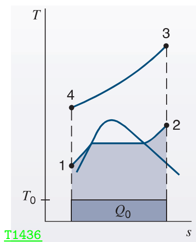
- $\Psi \equiv (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \cong (h - h_0) - T_0(s - s_0)$
- $\dot{w}_s = \dot{m}_1 h_1 - \dot{m}_2 h_{2s} - \dot{m}_3 h_{3s} = 25.27$ MW
- $\dot{w}_a = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = 20.18$ MW
- $\eta_I = \frac{\dot{w}_a}{\dot{w}_s} = 0.799$ ◀
- $\Delta(\dot{m}\Psi) = \dot{m}_1\Psi_1 - \dot{m}_2\Psi_2 - \dot{m}_3\Psi_3 = 24.65$ MW
- $\eta_{II} = \frac{\dot{w}_a}{\Delta(\dot{m}\Psi)} = 0.819$ ◀

Boiler

Borgnakke, Ex. 8.6: ▷ Determine the second-law efficiency for this process and the irreversibility per kilogram of water evaporated. Assume, c_p of the products of combustion is 1.155 kJ/kg K.



T1111



T1436

- $\frac{m_{gas}}{m_{water}} = \left[\frac{h_2 - h_1}{h_3 - h_4}\right] = 3.685$ kg/kg
- $\epsilon = \frac{m_{gas}(\psi_2 - \psi_1)}{m_{water}(\psi_3 - \psi_4)} = 0.458$
- $I_{cv} = -\Delta\psi = 9.09$ kW