# Introduction to Aerospace Propulsion

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Lecture No - 16

# In the next lecture ...

- Solve problems from
  - Entropy
  - Carnot cycle
  - Exergy
  - Second law efficiency


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# Problem 1

- A heat engine receives reversibly 420 kJ/cycle of heat from a source at 327$^{o}$C and rejects heat reversibly to a sink at 27$^{o}$C. There are no other heat transfers. Consider three different rates of heat rejection (a) 210 kJ (b) 105 kJ and (c) 315 kJ. For each of these cases show which cycle is reversible, irreversible and impossible.


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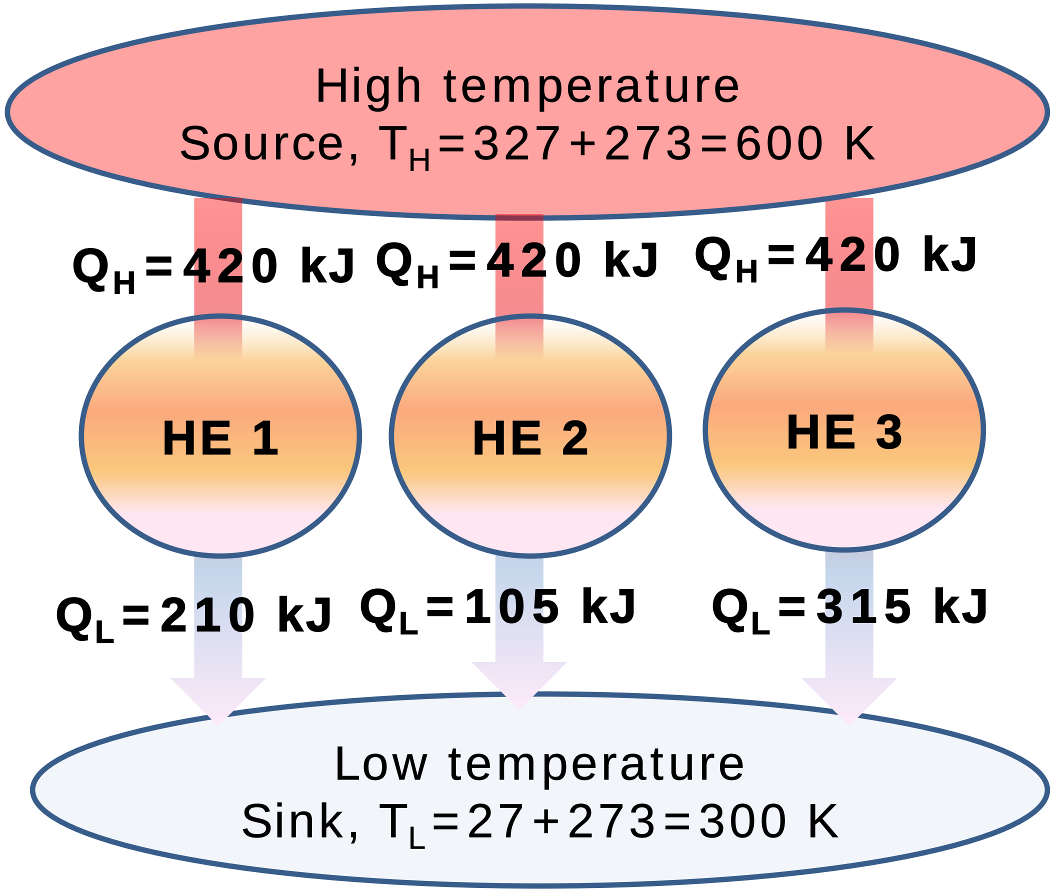
# Solution: Problem 1





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# Solution: Problem 1

- From the Clausius inequality, we have

$$\oint \frac{\delta Q}{T} \leq 0$$

For heat engine 1,

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = \frac{420}{600} - \frac{210}{300} = 0$$

$\therefore$ Heat engine 1 operates on a reversible cycle.



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# Solution: Problem 1

- We now look at heat engine 2.

For heat engine 2,

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = \frac{420}{600} - \frac{105}{300} = 0.35$$

Since $\oint \frac{\delta Q}{T} > 0$, the cycle is impossible.


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# Solution: Problem 1

- Heat engine 3

For heat engine 3,

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = \frac{420}{600} - \frac{315}{300} = -0.35$$

Since $\oint \frac{\delta Q}{T} < 0$, the cycle is irreversible and possible.


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# Problem 2

- A block of iron weighing 100 kg and having a temperature of 100$^o$C is immersed in 50 kg of water at a temperature of 20$^o$C. What will be the change in entropy of the combined system of iron and water? Specific heats of iron and water are 0.45 kJ/kg K and 4.18 kJ/kg K, respectively.


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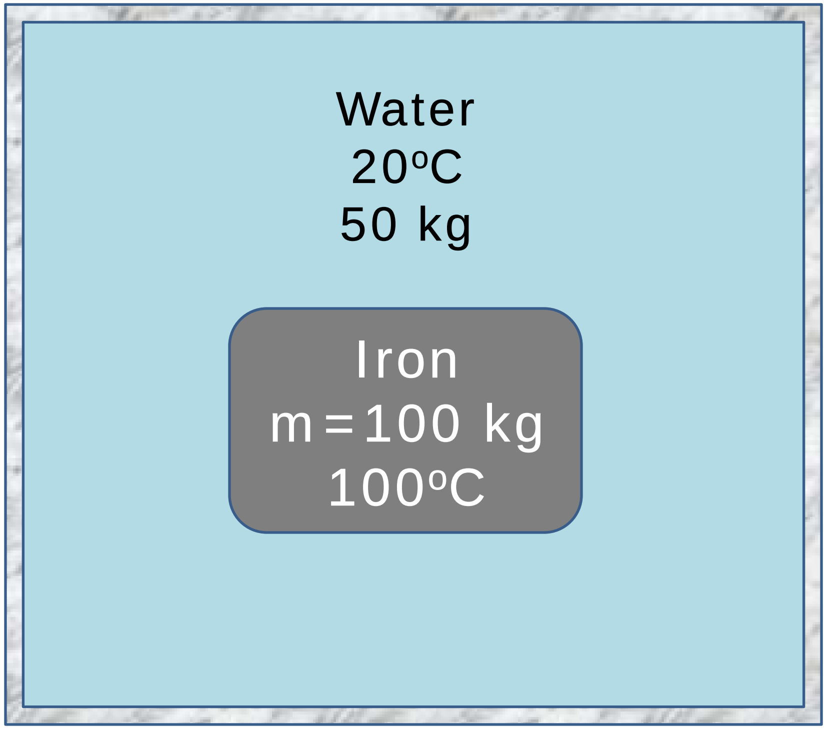
# Problem 2





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# Solution: Problem 2

- Let $T_f$ be the final temperature of the system after it reaches thermal equilibrium.
- From energy balance, we know that,

$$\{m \times cp \times (T-T_f)\}_{iron} = \{m \times cp \times (T_f-T)\}_{water}$$

$$100 \times 0.45 \times 10^3 (373-T_f) = 50 \times 4.18 \times 10^3 (T_f - 293)$$

$$T_f = 307.3\ K$$


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# Solution: Problem 2

$\Delta S_{total} = \Delta S_{iron} + \Delta S_{water}$

- We know that for solids and liquids, dV=0

$\Delta S = m \times c \times \ln T_f/T$

$\Delta S_{iron} = 100 \times 0.45 \times 10^3 \ln(307.3/373)$

$= -8.7189$ kJ/K (Why is this negative?)

$\Delta S_{water} = 50 \times 4.18 \times 10^3 \ln(307.3/293)$

$= 9.9592$ kJ/K

$\Delta S_{total} = -8.7189 + 9.9592 = 1.2403$ kJ/K


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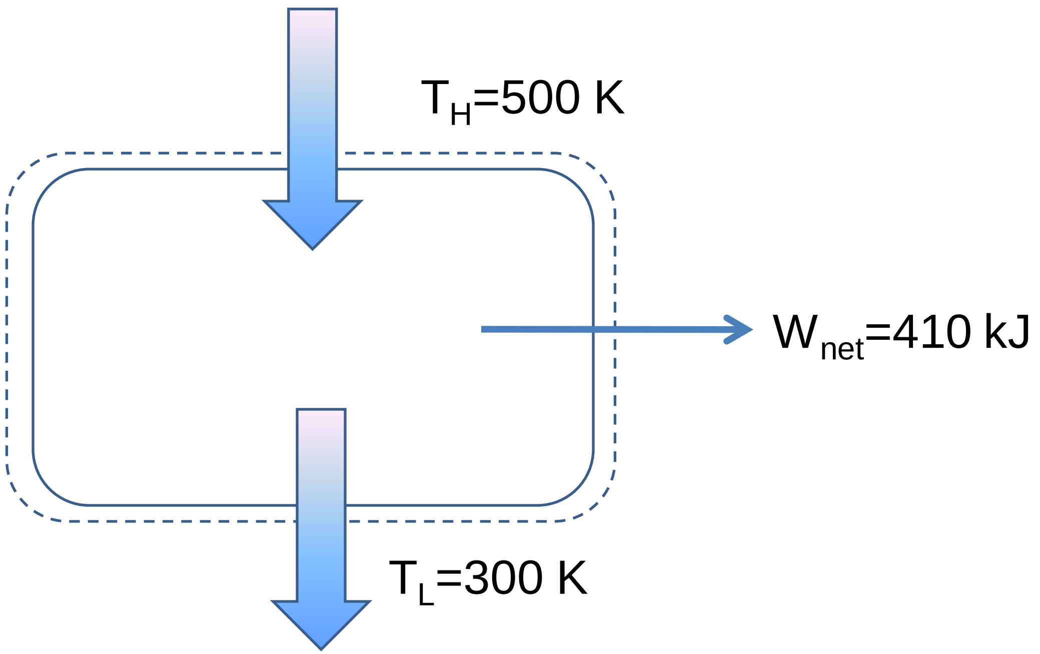
# Problem 3

- An inventor claims to have developed a power cycle capable of delivering a net work output of 415 kJ for an energy input by heat transfer of 1000 kJ. The system undergoing the cycle receives heat from a source of 500 K and rejects heat to a sink of 300 K. Determine if this is a valid claim.

# Solution: Problem 3



# Solution: Problem 3

- We know that efficiency of the cycle

$$\eta_{th} = W_{net}/Q_H$$
$$= 415/1000 = 0.415 \text{ or } 41.5\%$$

- The maximum efficiency that any cycle can have while operating between $T_H$ = 500 K and $T_L$ = 300 K is given by the Carnot efficiency.

$$\eta_{max} = 1 - T_L/T_H = 1 - 300/500$$
$$= 0.40 \text{ or } 40\%$$

Since $\eta_{th} > \eta_{max}$, the claim is not feasible.



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# Problem 4

- A heat pump is to be used to heat a house during the winter. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 120,000 kJ/h when the outside temperature drops to -7°C. Determine the minimum power required to drive this heat pump.


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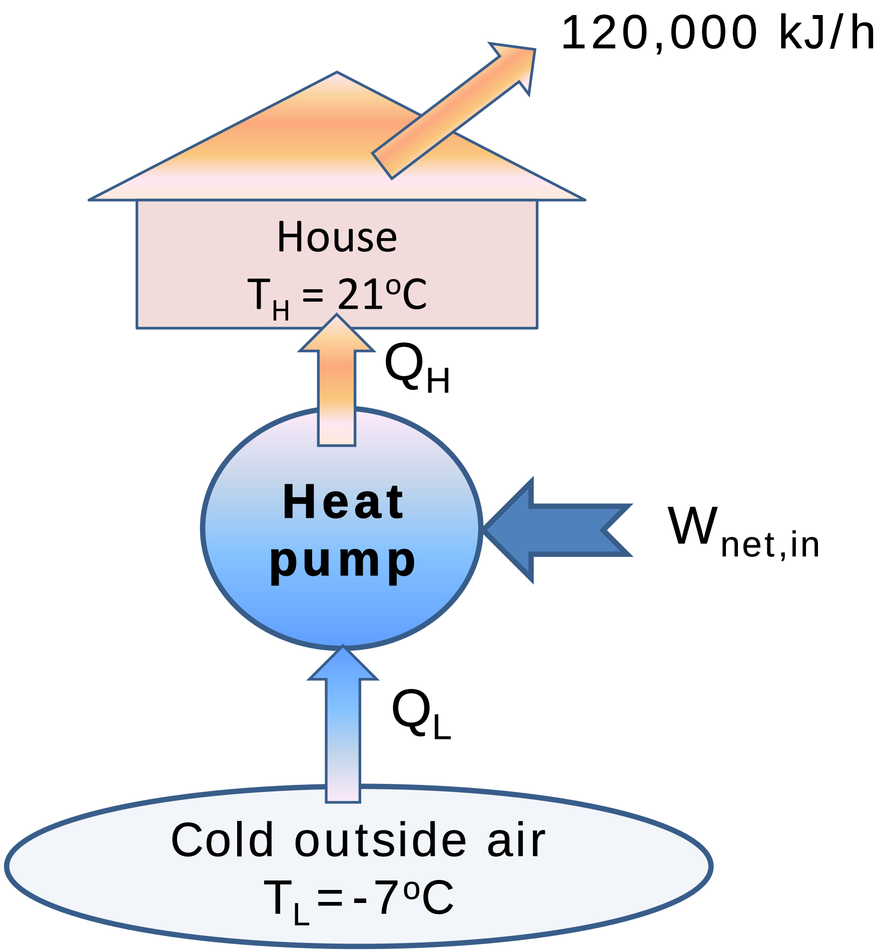
# Solution: Problem 4





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# Solution: Problem 4

- The heat pump must supply heat to the house at a rate of

$$Q_H = 120{,}000 \text{ kJ/h}$$
$$= 120{,}000/3600 \text{ kJ/s} = 33.3 \text{ kW}$$

- The power required will be minimum when the heat pump operates on a reversible cycle.
- The COP for such a cycle is

$$COP_{HP} = \frac{1}{1 - T_L / T_H}$$


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# Solution: Problem 4

- The COP for such a cycle is

$$COP_{HP} = \frac{1}{1 - T_L / T_H} = \frac{1}{1 - (-7 + 273)/(21 + 273)} = 10.5$$

- The minimum required power,

$$W_{net,in} = Q_H / COP_{HP} = 33.3/10.5$$
$$= 3.17 \text{ kW}$$


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# Problem 5

- Air flows through an adiabatic compressor at 2 kg/s. The inlet conditions are 1 bar and 310 K and the exit conditions are 7 bar and 560 K. Determine the net rate of exergy transfer and the irreversibility. The ambient temperature can be taken as 298 K, the specific heat at constant pressure for air is 1.005 kJ/kgK and the gas constant for air is 0.287 kJ/kgK.


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# Solution: Problem 5

- Exergy change per unit mass is

$$\psi = (h_2 - h_1) - T_0(s_2 - s_1) \text{ (Assuming KE, PE} \cong 0)$$

$$= c_p(T_2 - T_1) - T_0(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1})$$

$$= 1.005(560 - 310) - 298(1.005\ln\frac{560}{310} - 0.287\ln\frac{7}{1})$$

$$= 240.58 \text{ kJ/kg}$$


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# Solution: Problem 5

$$\Psi = \dot{m}\psi = 2 \times 240.58\,\text{kJ/kg} = 481.16\,kW$$

- Net rate of exergy change is 418.16 kW
- The actual work required is

$$W_{act} = \dot{m}(h_2 - h_1) = \dot{m}\,c_p(T_2 - T_1)$$

$$= 2 \times 1.005 \times (560 - 310) = 502.5\,kW$$


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# Solution: Problem 5

- Therefore Irreversibility,

$$I = W_{act} - \text{Exergy}$$
$$= 502.5 - 481.2$$
$$= 21.3 \text{ kW}$$

- Why is actual work higher than exergy?


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# Problem 6

- A pipe carries a stream of a liquid with a mass flow rate of 5 kg/s. Because of poor insulation the liquid temperature increases from 250 K at the pipe inlet to 253 K at the exit. Neglecting pressure losses, calculate the irreversibility rate associated with the heat leakage. Take $T_0$ as 293 K and specific heat for the liquid as 2.85 kJ/kg K.


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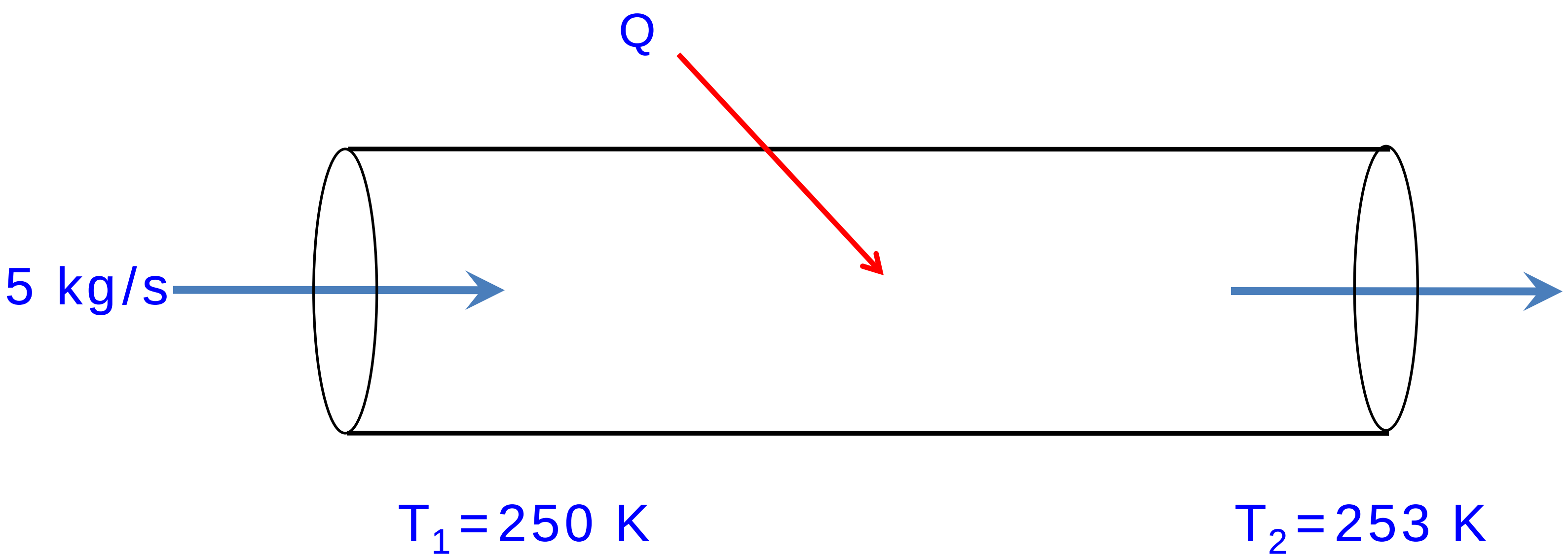
# Solution: Problem 6





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# Problem 6

- Rate of heat transfer to the liquid:

$$\dot{Q} = \dot{m} \times c \times (T_2 - T_1)$$
$$= 5 \times 2.85 \times (253 - 250)$$
$$= 42.75\, kW$$

- Rate of entropy increase of the liquid:

$$\Delta \dot{S}_{sys} = \dot{m} \times c \times \ln \frac{T_2}{T_1}$$
$$= 5 \times 2.85 \times \ln \frac{253}{250} = 0.17\, kW / K$$


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# Problem 6

- Rate of entropy decrease of the surroundings:

$$\Delta \dot{S}_{surr} = \frac{Q}{T_0} = \frac{-42.75}{293} = -0.1459\, kW/K$$

- Hence, rate of entropy increase of the universe:

$$\Delta \dot{S}_{univ} = \Delta \dot{S}_{sys} + \Delta \dot{S}_{surr}$$

$$= 0.17 - 0.1459 = 0.0241\, kW/K$$



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# Problem 6

- Therefore Irreversibility, I

$$I = T_0 \Delta \dot{S}_{univ}$$
$$= 293 \times 0.0241 = 7.06\, kW$$

- The irreversibility associated with this process is 7.06 kW.


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# Exercise Problem 1

- Air is compressed steadily by a 5 kW compressor from 100 kPa and 17°C to 600 kPa and 167°C at a rate of 1.6 kg/min. During this process, some heat transfer takes place between the compressor and the surrounding medium at 17°C. Determine the rate of entropy change of air during this process.
- Ans: 0.0025 kW/K

# Exercise Problem 2

- An adiabatic vessel contains 3 kg of water at 25$^o$C. By paddle wheel work transfer, the temperature of water is increased to 30$^o$C. If the specific heat of water is 4.18 kJ/kgK, find the entropy change of the universe.
- Ans: 0.139 kJ/K


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# Exercise Problem 3

- An inventor claims to have developed an engine that takes in 105 MJ at a temperature of 400 K, rejects 42 MJ at a temperature of 200 K and delivers 15 kWh of mechanical work. Is this a feasible engine?
- Ans: No as $\eta_{th} > \eta_{rev}$


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# Exercise Problem 4

- Air enters a nozzle steadily at 300 kPa and 87°C with a velocity of 50 m/s and exits at 95 kPa and 300 m/s. The heat loss from the nozzle to the surrounding medium at 17°C is estimated to be 4 kJ/kg. Determine (a) the exit temperature and (b) the exergy destroyed during this process.
- Ans: (a) 39.5°C, (b) 58.4 kJ/kg


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# Exercise Problem 5

- An iron block of unknown mass at 85°C is dropped into an insulated tank that contains 100 L of water at 20°C. At the same time, a paddle wheel driven by a 200-W motor is activated to stir the water. It is observed that thermal equilibrium is established after 20 min with a final temperature of 24°C. Assuming the surroundings to be at 20°C, determine (a) the mass of the iron block and (b) the exergy destroyed during this process.
- Ans: (a) 52.0 kg, (b) 375 kJ


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# Exercise Problem 6

- An adiabatic turbine receives gas ($c_p$=1.09 kJ/kg K and $c_v$=0.838 kJ/kgK) at 7 bar and 1000$^o$C and discharges at 1.5 bar and 665$^o$C. Determine the second law efficiency of the turbine assuming $T_0$=298 K.
- Ans: 0.879


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# In the next lecture ...

- Gas power cycles
- The Carnot cycle and its significance
- Air-standard assumptions
- An overview of reciprocating engines
- Otto cycle: the ideal cycle for spark-ignition engines
- Diesel cycle: the ideal cycle for compression-ignition engines
- Dual cycles


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