Grading: 35 points. If the assignment is submitted to Isidore after the due date without a valid reason (to be discussed with professor well before due date) then 50% will be **automatically** deducted from the assignment.

All work should be submitted as a well-written, concise report with all equations presented using an equation editor (Word equation editor, Latex, or MathType suggested). Submit a .pdf of all of your work to Canvas and submit any MATLAB / EXCEL / ChatGPT files used during calculations as a file submission (codes will be tested to ensure they run). No plagiarism is permitted. If plagiarism is discovered, an automatic 0 for the assignment will be applied.

General Theory and Applications

1. What is the number of independent, intensive properties required to determine the **state** of a system.
   a) 1
   b) 2
   c) 3
   d) All of them

2. Match each type of system with their respective definition by writing by writing the letter of the respective definition (from the "Definitions" list) in the given parenthesis.

   Concepts

   - Closed system (control mass) ( )
   - Open system (control volume)( )
   - Isolated system ( )

   Definitions

   a) No mass can cross the boundary of the system
   b) No mass nor energy can cross the boundary of the system
   c) Mass can cross the boundary of the system

3. Select the appropriate ways in which mass can carry energy across a system boundary
   a) Internal energy
   b) Kinetic energy
   c) Mass flow
   d) Flow work
   e) Potential energy
   f) Electrical energy

4. Solids and fluids both resist shear stress by static deflection
   a) True
   b) False

5. The mass flow rate flowing through a cross-sectional area A_c can be calculated as

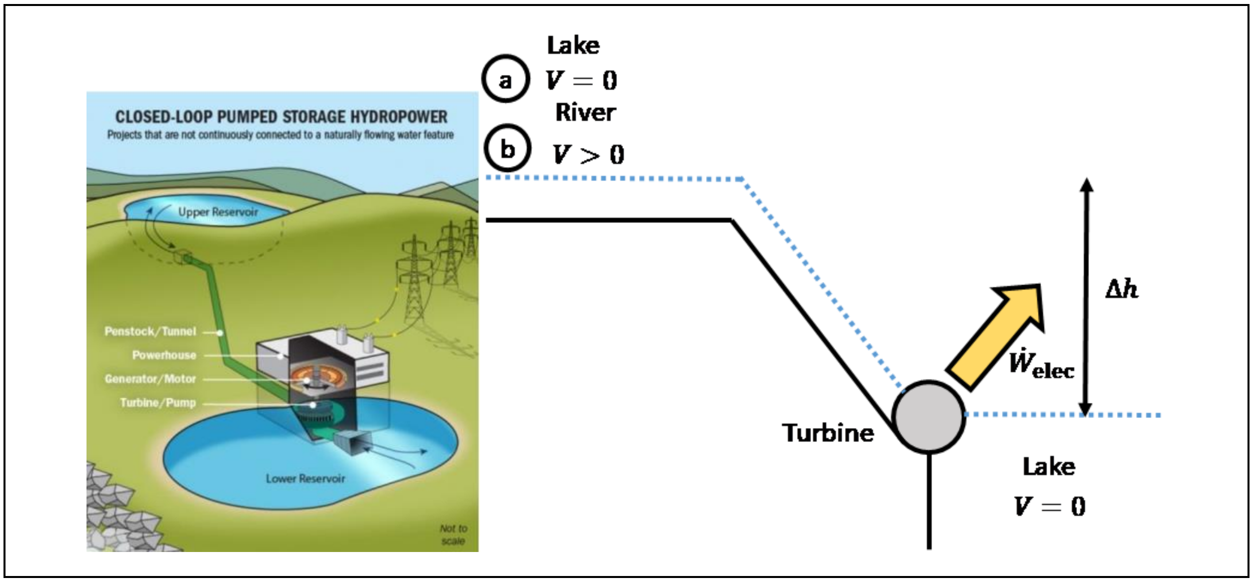
a) ρA_c
b) $(\dot{m}_{\text{in}} + \dot{m}_{\text{out}})/2$
c) $\rho V_n A_c$
d) $\rho \vec{V} A_c$

First Law Applications

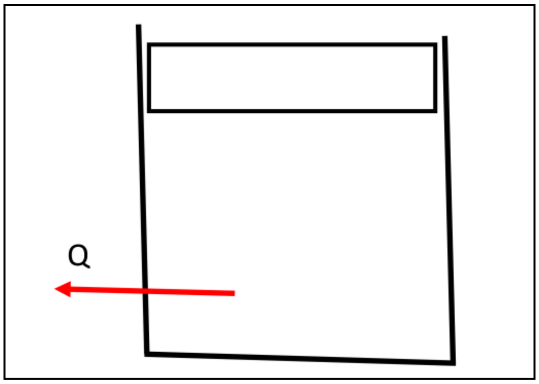
6. A pumped hydro storage system is drained to extract stored energy on-demand. Water is drained toward a lower lake and a volumetric flow rate of 500 m^3/s with an 85 m drop in elevation.

a. Determine the maximum possible power that could be extracted from the system as it flows into the lake using a turbine **assuming** that the upper reservoir is a lake with a velocity of 0 m/s.

b. Determine the maximum possible power that could be extracted from the system as it flows into the lake using a turbine **assuming** that the upper reservoir is a river with an average velocity of 3.75 m/s. What is the percent increase in possible power output from part a. Explain **physically** why this increase is observed.



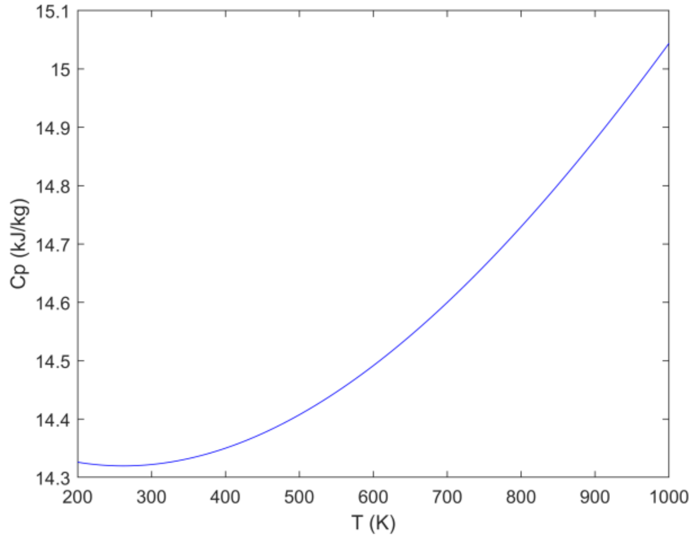
7. A piston-cylinder system is filled with 3.8 kg of H2 gas (R = 4.124 kJ/kg-K) and is initially at 250 kPa and 900 K. Heat is removed from the system until it reaches 400 K. Cv(T) and Cp(T) are plotted as functions of temperature for this gas.

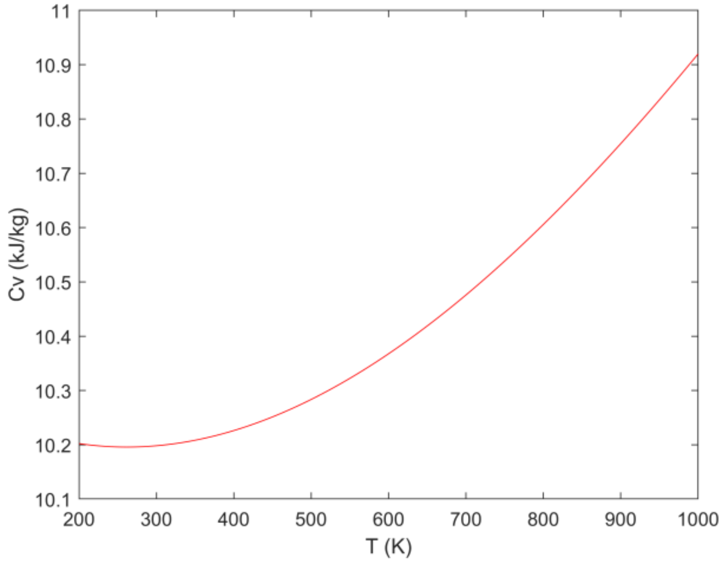


Part A: Find the change in volume (m^3) of the system.

Part B: Find the magnitude (kJ) and direction (in or out of system) of the boundary work during this process. Defend why your answer makes sense.

Part C: Calculate the change in specific enthalpy (kJ/kg) and internal energy (kJ/kg) of the gas during this process using the given property tables.

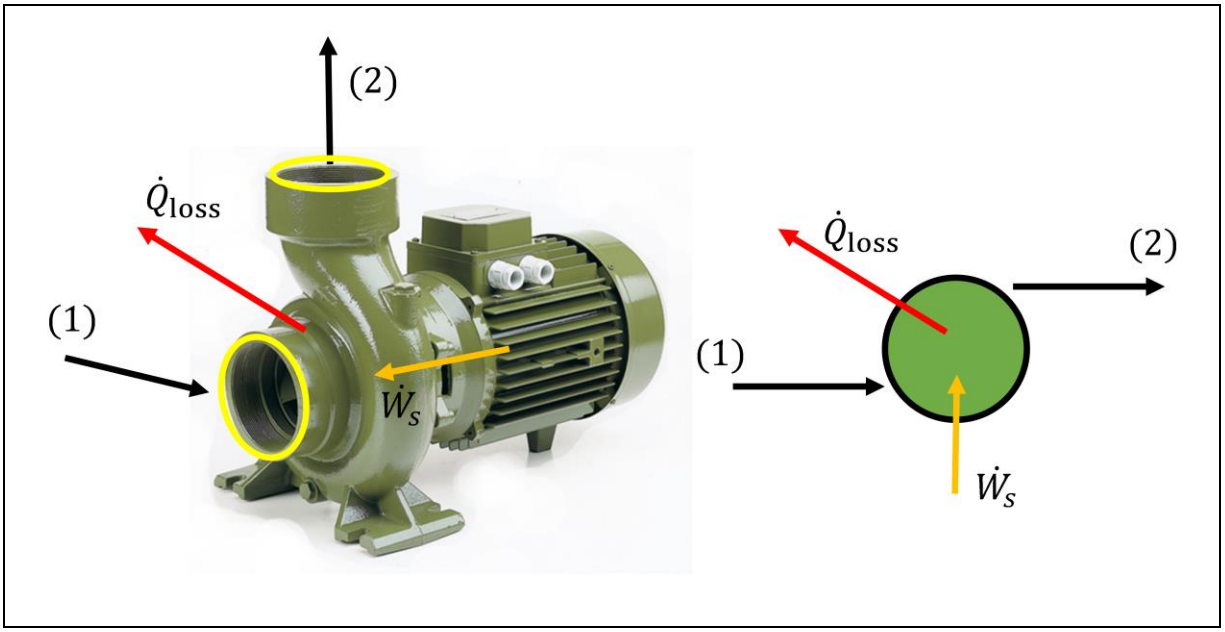




8. A centrifugal pump is operated steadily and consumes 10 kW of shaft work to move water (1000 kg/m^3, C = 4.2 kJ/kg-K) at a mass flow rate of 0.05 kg/s. The pump is not very well insulated. Temperature is measured at the inlet (20 oC) and the outlet (45 oC) of the pump. The cross sectional area at the inlet and the outlet of the pump is the same (A2 = A3). Note: For this application, assume that the liquid water remains far away from the vapor dome during the process `and can be considered an incompressible substance.

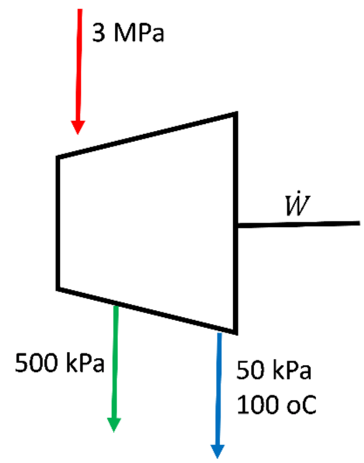
PART A: Using conservation of mass, prove that the change in kinetic energy is negligible for the water in this pump.

PART B: Using conservation of energy, estimate the heat loss (kW) from the pump.



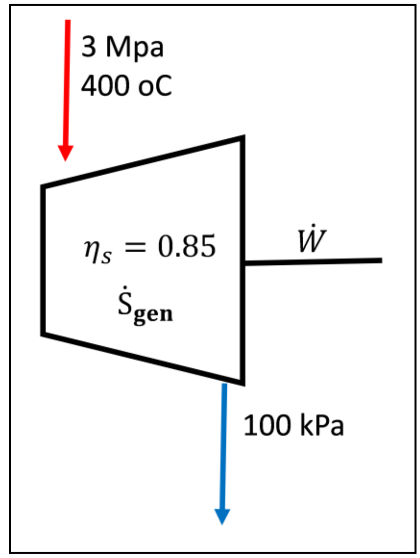
Isentropic Steady Flow Machines

9. A well-insulated steam turbine is operating reversibly with 3 kg/s of steam at a pressure of 3 MPa. The majority of the steam is exhausted at 50 kPa and 100°C. However, 12 percent of this flow is diverted within the steam turbine to provide preheating for other cycle components once the inlet stream was expanded to 500 kPa. Determine the power produced by this turbine, in kW.



Real Devices and Entropy "Balances"

10. A steam turbine is operating steadily and expands a 2.5 kg/s stream of steam/water from 3 MPa and 400 oC to 100 kPa. Assume the turbine is well-insulated. The manufacturer performance curves indicate that under these conditions, the turbine would operate with an isentropic efficiency of 0.85. Determine the following:



PART A: What is the outlet temperature (K), enthalpy (kJ/kg), quality, and entropy (kJ/kg-K) of the water / steam stream if the turbine operated **isentropically?**

PART B: What is the **real** outlet temperature (K), enthalpy (kJ/kg), quality, and entropy (kJ/kg-K) of the water / steam?

PART C: Calculate and compare the differences between the output turbine work for isentropic versus real operation. Do the differences make sense? Why?

PART D: Due to irreversibilities in the real expansion process, entropy is generated in the universe, meaning that the disorder of the energy in the water/steam has increased. To design better engineering devices, engineers often track the rate of entropy generation ($\dot{S}_{\text{gen}}$) introduced by a device. The ideal process would include $\dot{S}_{\text{gen}} = 0$, where there are no irreversibilities. We can track this generation rate by using the entropy "balance" (a new physical law), shown below for an open system:

$$\frac{\sum \dot{Q}}{T_{\text{boundary}}} + \sum \dot{m} \cdot s_{in} - \sum \dot{m} \cdot s_{\text{out}} + \dot{S}_{\text{gen}} = \frac{d(S_{\text{sys}})}{dt}$$

Using the above equation, what kind of process is derived for a steady flow, well-insulated, irreversible process?

Using the above equation, calculate the $\dot{S}_{\text{gen}}$ for the real process modeled in part B.

PART E: While minimizing $\dot{S}_{\text{gen}}$ is good to improve system performance, the inclusion of irreversiblities actually has a small benefit to the performance of a turbine. Turbomachinery, like turbines, will be damaged if a two-phase fluid is expanded through them. The amount of water droplets in the water/steam stream will hit the turbine blades and erode them over time. **Compare the properties in PART A and PART B and identify a benefit of having a non-ideal turbine?**

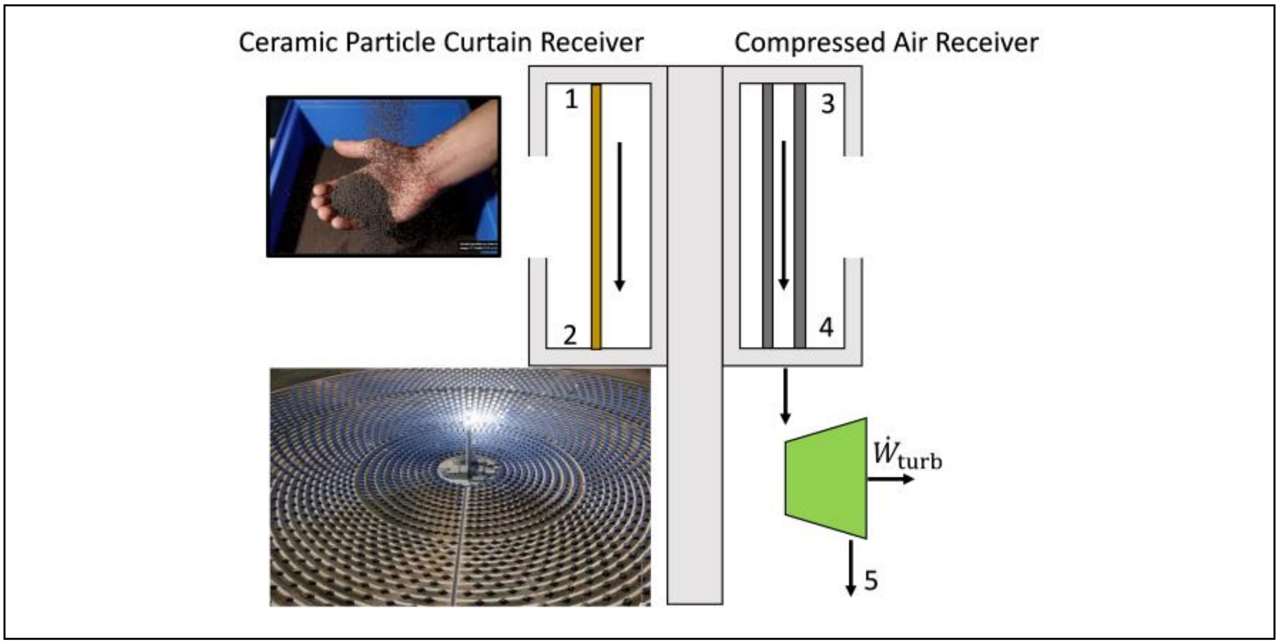
Entropy Changes of a Pure Substance

11. A free piston-cylinder device is filled with 3 kg of a saturated liquid-vapor mixture of water/steam at 200 kPa. The exterior of the tank may be assumed to be well-insulated. **Initially**, 40% of the mass is in the liquid phase (**hint: quality**). Heat is supplied via an electric resistance heater until all the liquid in the tank is evaporated. Determine the **specific** entropy change (Δs, kJ/kg-K) of the steam inside the tank during this process.

12. A piston–cylinder device is well insulated and contains 4.8 L of saturated liquid ($x = 0$) water at 150 kPa. The piston moves freely within the cylinder. An electric resistance heater inside the cylinder is suddenly turned on, and 1700 kJ of energy is delivered to the steam. Determine the **total** entropy change (ΔS, kJ/kg) of the steam in the device during this process.

Real Devices and Entropy Changes of Incompressible Substances and Ideal Gases

13. Two solar receivers are proposed for storing concentrated solar energy as heat in either solid ceramic particles (CARBOBEAD CP, ρ = 3270 kg/m3 and C ~ 1.3 kJ/kg-K up to 1100 oC) or compressed air. Both receivers are designed to heat their respective materials from 250 oC to 1100 oC. Compressed air is introduced into the one receiver at a mass flow rate of 0.75 kg/s, 250 oC, and 4000 kPa. The heated air in the receiver is then expanded reversibly through a well-insulated turbine to an environmental pressure of 100 kPa. Assume table A-17 is populated with a reference state of 0K and 100 kPa and the gas constant for air is 0.287 kJ/kg-K. NOTE: I have not provided all of the assumptions needed to correctly solve this problem. Make sure you clearly label additional assumptions used to solve the problem.



Determine the following:

PART A: Change in specific entropy (kJ/kg-K) of the particle curtain from 1 -> 2

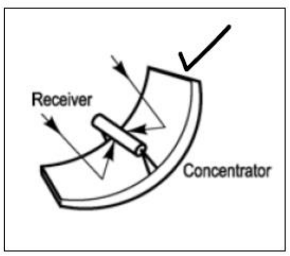
PART B: Change in specific entropy (kJ/kg-K) of the compressed air stream from 3-> 4

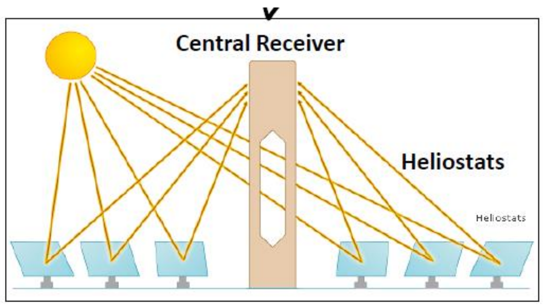
PART C: Specific entropy (kJ/kg-K) of the compressed air stream for state 4

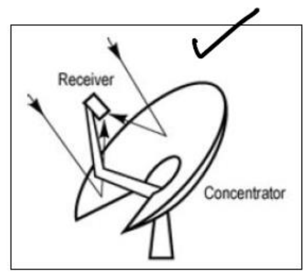
PART D: Work (kW) produced via the turbine from 4 -> 5

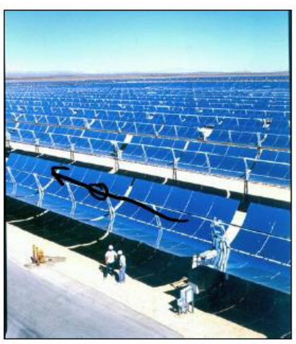
Carnot Cycle Heat Engines

14. The performance of an ideal concentrated solar power plant can be modeled as the combined efficiency of a 1) solar receiver and 2) Carnot heat engine. The solar receiver is an engineered device to absorb concentrated solar resources and deliver them as heat to a power cycle. The optimal performance of the solar receiver is limited by the receiver temperature, as at too high of temperatures a large portion of the absorbed energy is re-radiated and lost to the environment. Additionally, the solar receiver performance is limited by how well the concentrating infrastructure (mirrors, lenses, etc.) can concentrate incident irradiation from the sun. State of the art concentrating infrastructures achieve concentration ratios (C) exceeding 1000 suns, or capable of delivering solar resources to the receiver 1000 times more intense than a sunny day. The solar receiver acts as the high-temperature thermal reservoir for a heat engine. As a result, the total ideal system efficiency is the product of the receiver efficiency and the heat engine efficiency in converting incident solar resources into work.

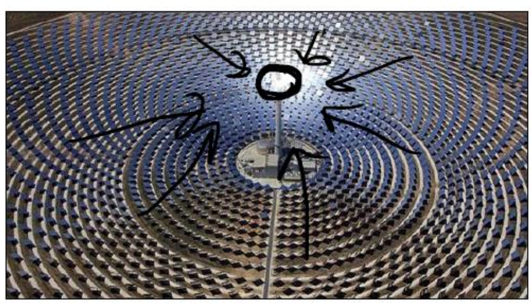








$C \sim 100$ suns



$C \sim 1{,}000 - 2{,}000$ suns

$C \sim 3{,}000$ suns

PART A: Using the equations below, plot the total efficiency for a given concentrating system (C – 100, 500, 1000, 2000, and 3000 suns) for possible high-temperature thermal reservoir temperatures (300->2600 K). Present the plot below and submit code.

MATLAB Resources:

[2-D line plot - MATLAB plot (mathworks.com)]

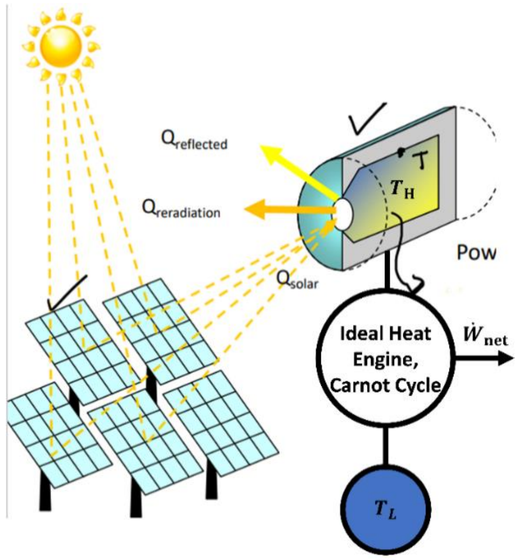
[Label x-axis - MATLAB xlabel (mathworks.com)]

[Label y-axis - MATLAB ylabel (mathworks.com)]

[Add legend to axes - MATLAB legend (mathworks.com)]

[Retain current plot when adding new plots - MATLAB hold (mathworks.com)]

PART B: Identify and comment on the optimal receiver operating temperature required to maximize total system efficiency for a given solar concentrating infrastructure (C).



$$\eta_{\text{receiver}} = 1 - \frac{\sigma T^4}{C \cdot I}$$

$$= 1 - \frac{5.67 \cdot 10^{-8} \left(\frac{W}{m^2 K^4}\right) \cdot T_{\text{H}}^4}{C \cdot 1000 \left(\frac{W}{m^2}\right)}$$

$$\eta_{\text{Carnot,HE}} = 1 - \frac{T_L}{T_H}$$

$$\boldsymbol{\eta_{\text{Total}} = \eta_{\text{receiver}} \cdot \eta_{\text{Carnot,HE}}}$$