2] You are a particularly bright caveman tired of living in an unheated and unlighted cave. In front of your cave there are 2 geysers (continuously flowing fountains of hot water). Geyser A puts out 1 kg/s of water at a temperature of 310 K while geyser B puts out 0.15 kg/s of water at a temperature of 370 K. The ambient temperature is 290 K.

Geyser A: 1 kg/s of water at 310 K

Geyser B: 0.15 kg/s of water at 370 K

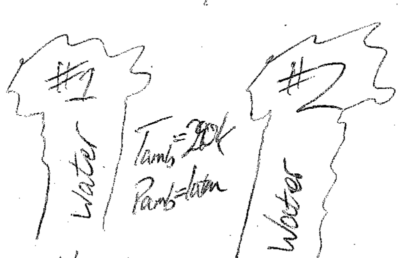
a. If you wanted to heat your house using one of the geysers which one would you choose and why? Justify your decision with the appropriate calculations.

b. If you wanted to use one of the geysers to power a heat engine that could be used to produce work (to break rocks for example) then which geyser would you choose and why? Again justify your answer with the appropriate calculations.

Availability/Exergy of an energy resource

- Up until now our second law analysis have focused on quantifying entropy, calculating the entropy generated & determining efficiencies for components & systems. We really have not considered the resources that these components & systems utilize.
- Anytime I have something that is not at the atmospheric/ambient conditions, I have a gradient that I can extract energy from & I can use this resource to produce useful work.
- The maximum amount of work that I could produce is sometimes referred to as the availability or exergy of the resource.

Show Geyser-Caveman Problem



$\dot{m}=1kg/s$
$T=310k$
$P=1atm$

$\dot{m}=0.15kg/s$
$T=370k$
$P=1atm$

A) If you wanted to heat your cave, which would you choose?

B) If you wanted to use one to power a heat engine (for breaking rocks or track lighting) which would you choose?

There are ~~2 ways~~ a couple of ways of doing this:

1) Draw system to maximize irreversibilities
2) Draw system to remove irreversibilities
3) Calculate Exergy directly

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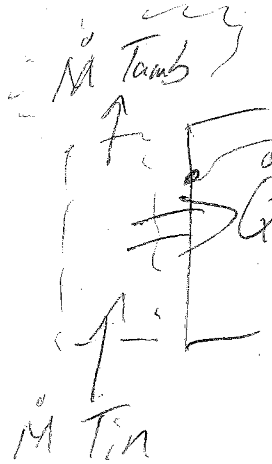
Let's find which Geyser is better for heating by maximizing irreversibility



Energy Balance: $\dot{E}_{in} = \dot{E}_{out} + \frac{dE_{stored}}{dt}$

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{M}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{M}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right)$$

$\dot{Q}_{out} = \dot{M}(h_{in} - h_{out})$ apply incompressible substance: $\dot{Q}_{out} = \dot{M}C_p(T_{in} - T_{out})$

Geyser A: $\dot{Q}_{out} = 1\,kg/s\,(4220\,J/kg\text{-}k)(310 - 290k) \Rightarrow \dot{Q}_{out} = 84{,}400\,W$

Geyser B: $\dot{Q}_{out} = 0.15\,kg/s\,(4220\,J/kg\text{-}k)(370 - 290k) \Rightarrow \dot{Q}_{out} = 50{,}640\,W$

$\Rightarrow$ A is better for heating

Entropy Balance: $\dot{S}_{in} + \dot{S}_{Gen} = \dot{S}_{out} + \frac{dS_{stored}}{dt}$

$$\dot{M}s_{in} + \dot{S}_{Gen} = \frac{\dot{Q}_{out}}{T_{amb}} + \dot{M}s_{out} \Rightarrow \dot{S}_{Gen} = \frac{\dot{Q}_{out}}{T_{amb}} + \dot{M}C\ln\left(\frac{T_{out}}{T_{in}}\right)$$

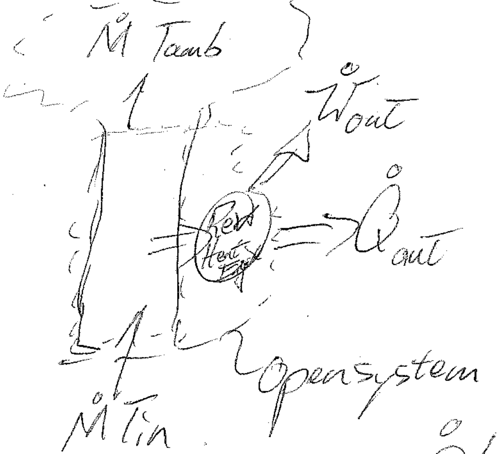
Geyser A: $\dot{S}_{Gen} = \frac{84{,}400\,W}{290k} + 1\,kg/s\,(4220\,J/kg\text{-}k)\ln\left(\frac{290k}{310k}\right) \Rightarrow \dot{S}_{GenA} = 9.597\,W/k$

Geyser B: $\dot{S}_{Gen} = \frac{50{,}640\,W}{290k} + 0.15\,kg/s\,(4220\,J/kg\text{-}k)\ln\left(\frac{290k}{370k}\right) \Rightarrow \dot{S}_{GenB} = 20.41\,W/k$

Geyser A provides 1.6x more heat than Geyser B

We'll come back to these

Lets find which geyser is better for producing work by ~~[illegible]~~ excluding all irreversibilities. How do we do this? Use a reversible device, a Carnot heat engine, to transfer heat. Heat transfer to & from a Carnot/reversible heat engine is by definition reversible.



Entropy Balance on Reversible system:

$$\dot{S}_{in} + \cancel{\dot{S}_{gen}} = \dot{S}_{out} + \cancel{\frac{dS_{stored}}{dt}}^{\,0} \Rightarrow \dot{M}s_{in} = \frac{\dot{Q}_{out}}{T_{amb}} + \dot{M}s_{out} \Rightarrow$$

$$\Rightarrow \dot{Q}_{out} = T_{amb}\dot{M}C_p \ln\left(\frac{T_{in}}{T_{amb}}\right) \xrightarrow{\text{Geyser A}} \dot{Q}_{revA} = 290k\left(1\tfrac{kg}{s}\right)\left(4220\tfrac{J}{kg \cdot k}\right)\ln\left(\frac{310k}{290k}\right) \Rightarrow \dot{Q}_{revA} = 81{,}617\,W$$

Geyser B: $\dot{Q}_{rev,B} = 290k\left(0.15\tfrac{kg}{s}\right)\left(4220\tfrac{J}{kg \cdot k}\right)\ln\left(\frac{370k}{290k}\right) \Rightarrow \dot{Q}_{revB} = 44722\,W$

Energy Balance on Reversible system: $\dot{E}_{in} = \dot{E}_{out} + \cancel{\frac{dE_{stored}}{dt}}^{\,0}$

$$\Rightarrow \cancel{\dot{Q}_{in}} + \cancel{\dot{W}_{in}} + \dot{M}_{in}\left(h_{in} + \cancel{\frac{v_{in}^2}{2}} + \cancel{gz_{in}}\right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{M}_{out}\left(h_{out} + \cancel{\frac{v_{out}^2}{2}} + \cancel{gz_{out}}\right)$$

$$\dot{M}_{in}h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{M}_{out}h_{out} \Rightarrow \dot{W}_{out} = \dot{M}C_p(T_{in} - T_{out}) - \dot{Q}_{out}$$

Geyser A: $\dot{W}_{out_A} = 1\tfrac{kg}{s}\left(4220\tfrac{J}{kg \cdot k}\right)(310k - 290k) - 81{,}617W \Rightarrow \dot{W}_{out,a} = 2783\,W$

Geyser B: $\dot{W}_{out,B} = 0.15\tfrac{kg}{s}\left(4220\tfrac{J}{kg \cdot k}\right)(370k - 290k) - 44722W \Rightarrow \dot{W}_{out,B} = 5918\,W$

Geyser B could do 2x the work as Geyser A!!

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Did I screw up? Geyser A has 1.6x more heat than B

but Geyser B can produce 2x more work than A?

Even though Geser B has $\approx \frac{1}{70}$ the mass flow rate of A, the higher temp gives B a much higher availability. Availability (Exergy) is the potential of a resource to produce useful work. It is directly related to entropy generated & the dead state conditions.

~~From Part A: $\dot{S}_{GenA}$~~ What do I mean by "dead state": when the resource is fully equilibrated with the surroundings, it is "dead" in terms of it's potential for work => No more gradients

From Part A: $\dot{S}_{Gen_A} = 9.597 \frac{W}{K}$ Availability $= \dot{S}_{Gen} T_0$ ← Dead state Temp

$$\text{Availability}_A = \dot{S}_{Gen_A} T_0 = 9.597 \frac{W}{K}(290K) = \underline{\text{Availability}_A = 2783W}$$

$$\text{Availability}_B = \dot{S}_{Gen_B} T_0 = 20.41 \frac{W}{K}(290K) = \underline{\text{Availability}_B = 5918W}$$

Nice way to check results, Part A is Consistent with part B.

Is there an easier way to do this?

Availability/Exergy =

$$\dot{W}_{Max} = \dot{M}(h_1 - h_{amb}) \quad \cancel{\dot{Q}_{max,rev}\ T_{amb}(S_1 - S_{amb})} \quad \dot{Q}_{max,rev} = \dot{M}\, T_{amb}(S_1 - S_{amb})$$

(h_{amb} = h_0, S_{amb} = S_0)

So the exergy of the flow is: $\dot{X} = \dot{M}\psi = \dot{M}\left[(h_1 - h_0) - T_0(S_1 - S_{0}) + \frac{v^2}{2} + gz\right]$

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Exergy is a property of a flow. Can we balance it? yes!

Our Original balance: IN + PRODUCED = OUT + DESTROYED + STORED

Exergy or availability to do work can be transferred into & out of Systems in three ways: 1) with work W, 2) with mass $\dot{m}\psi$, 3) with heat $\left(1-\frac{T_0}{T}\right)\dot{Q}$

→ Can Exergy be produced? → Sadly No → we cannot produce availability

→ Can Exergy be destroyed? → Absolutely → if we don't carefully control our energy we loose it forever.

→ Can we store Exergy? → yes

Exergy Balance: Incremental

$$X_{in} = X_{out} + X_{destroyed} + \Delta X_{stored}$$

Exergy Balance: On Rate basis

$$\dot{X}_{in} = \dot{X}_{out} + \dot{X}_{destroyed} + \frac{dX_{stored}}{dt}$$

for an open system $X = M\psi = M\left[(h_1 - h_0) - T_0(s_1 - s_0) + \frac{v^2}{2} + gz\right]$

for a closed system $X = M\psi = M\left[(u_2 - u_0) + P_0(v_2 - v_0) - T_0(s_1 - s_0)\right]$

$X_A = \dot{M}\psi = \dot{M}\left[C_p(T_{in} - T_{amb}) - T_{amb} C_p \ln\left(\frac{T_{in}}{T_{amb}}\right)\right] = 2783W$ $X_B = 5918W$

Think Thermodynamically. → It saves Exergy!