Thermodynamics PhD Qualifying Exam
Information Sheet and Instructions

Objective

PhD candidates should demonstrate understanding of the thermodynamic topics listed below by using them to formulate and solve complex engineering problems based on real world challenges, critically analyze solutions and make fact based arguments. The fundaments covered in the exam are those typically covered in an undergraduate thermodynamics course, and candidates should expect questions where the solution requires synthesis of multiple thermodynamic concepts or requires the use of thermodynamic principles to produce logical, evidence-based analyses and conclusions. This exam is meant to assess the PhD Program Outcomes of *subject mastery* and *independent learning.*

Instructions

- The exam is open book, but it is expected that the book will be used primarily for referencing thermodynamic tables.
- Exams will typically contain 2 – 3 problems that are weighted as shown on the exam.
- Typically, a score of 70% or higher is required to pass the exam with at least 50% in each topical area; Conservation of mass, Property Determination, Conservation of Energy, Entropy, and Cycles.
- A numerical answer is far less important than the process. Solutions are expected to contain the following elements:
    - The analysis should proceed logically from one step to the next
    - A clear statement of any assumptions
    - Any simplifications should be justified
    - Conclusions should be persuasively articulated.
- Calculators are allowed; however, cell phones and other electronic devices are not permitted in the exam room.
- The exam has a time limit of 2.0 hours.
- Each problem should be worked on a separate sheet of paper.
- The student's name should appear on each sheet.

Exam Topics and Learning Objectives

The topics covered by the exam include:

1. Application of the principle of conservation of mass to open systems undergoing both transient and steady processes.
2. Use of the state postulate to fix the state of a system. Candidates are expected to use appropriate property relationships and tables to find property values for ideal gases, superheated vapors, saturated liquid-vapor mixtures and incompressible substances.
3. Application of the principle of conservation of energy (1^{st} law of thermodynamics) to closed systems and to open systems undergoing both steady and transient processes.

4. Application of the principle of increasing entropy (2^{nd} law of thermodynamics) to closed systems and to open systems undergoing both steady and transient processes.
5. Analysis of thermodynamic cycles. Candidates are expected to be able to analyze any cycle of specified processes and the canonical power cycles (Otto, Diesel, Brayton, Rankine) and vapor compression refrigeration cycles.

Topics not covered include:

1. Exergy and Availability
2. Mixtures
3. Humidity, Psychometric Chart
4. Chemical Reactions
5. Equilibrium
6. Compressibility

Representative courses at BYU:	MeEn 321: Thermodynamics
Representative texts:	Cengel and Boles, *Thermodynamics: An Engineering Approach*
	Moran and Shapiro, *Fundamentals of Engineering Thermodynamics*

Additional Courses that provide a helpful review of some of the MeEn 321 topics but include additional topics that are not covered in the exam include: MeEn 422, MeEn 425, MeEn 426

SAMPLE PROBLEMS

Sample Exam #1 – Winter 2018

(50 pts) 1. Imagine a friend asks you about an advertisement for a new refrigerator. The advertisement touts the benefits of a lower-pressure condenser. In this system, the R-134a in the condenser coils operates at a pressure of 550 kPa instead of the typical 1.7 MPa. The advertisement claims the lower operating pressure makes the condenser safer and less expensive to manufacture and operate. Based on thermodynamic principles, determine whether you would recommend purchasing this refrigerator. Clearly and concisely articulate the logic used to formulate your recommendation.

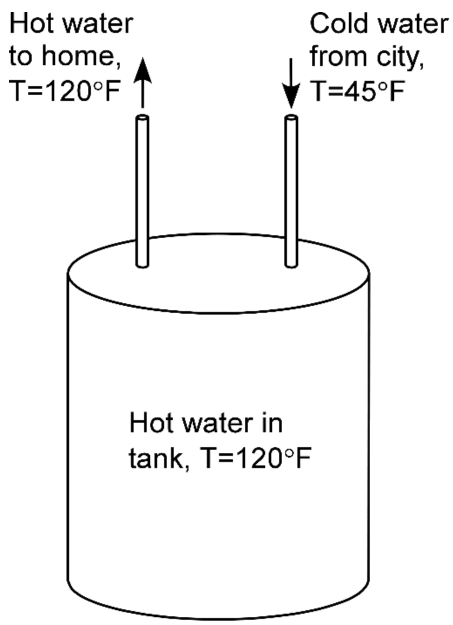
(50 pts) 2. A device called a "tank extender" is being sold as a way of increasing the capacity of a home water tank. A standard hot water tank, and a tank with an extender are shown below. The standard tank must keep water below the scalding temperature of water, 120°F (48.9°C). The extender allows the water to be heated to the maximum temperature of 160°F (71.1°C) and then uses a control mechanism to mix hot water from the tank with cold water from the city water supply to a temperature of 120°F. Assuming the cold water enters both tanks at the bottom and does not mix at all with the hot water that exits out the top, use the data below and evaluate the tank extender with respect to the following questions: How long will the extender increase the flow of hot water for a shower? Does the extender increase entropy generation? What are the thermodynamic pros and cons of a tank extender?

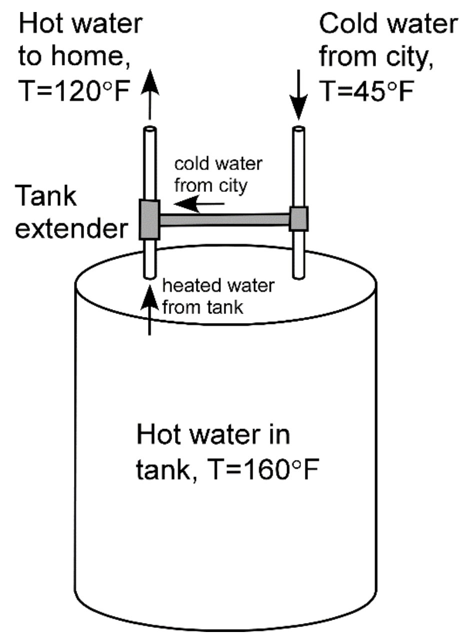
Data:

Tank Volume: 40 gallons

Shower flow rate: 2 gal/min

Desired shower temperature: 110°F (43°C)



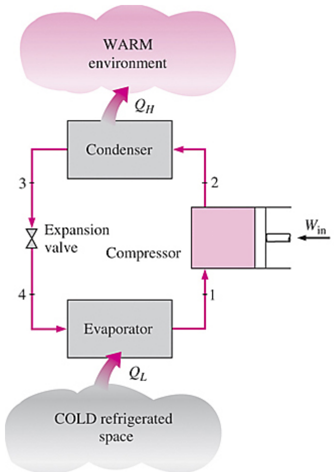


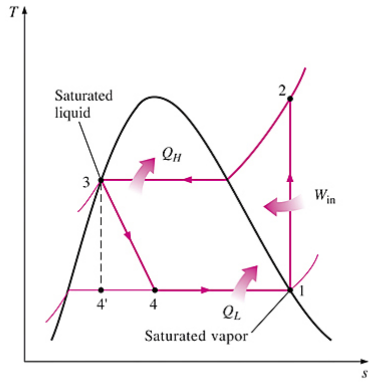
Sample Exam 1 Solutions

1. Known: A refrigerator operates with a condenser pressure of 550 kPa rather than the typical 1.7 MPa.

Find: Recommend whether the refrigerator should be purchased.

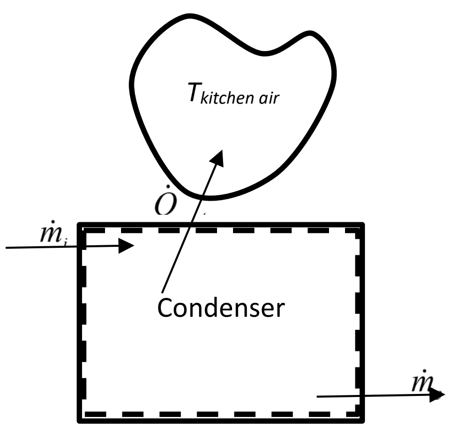
Schematic:





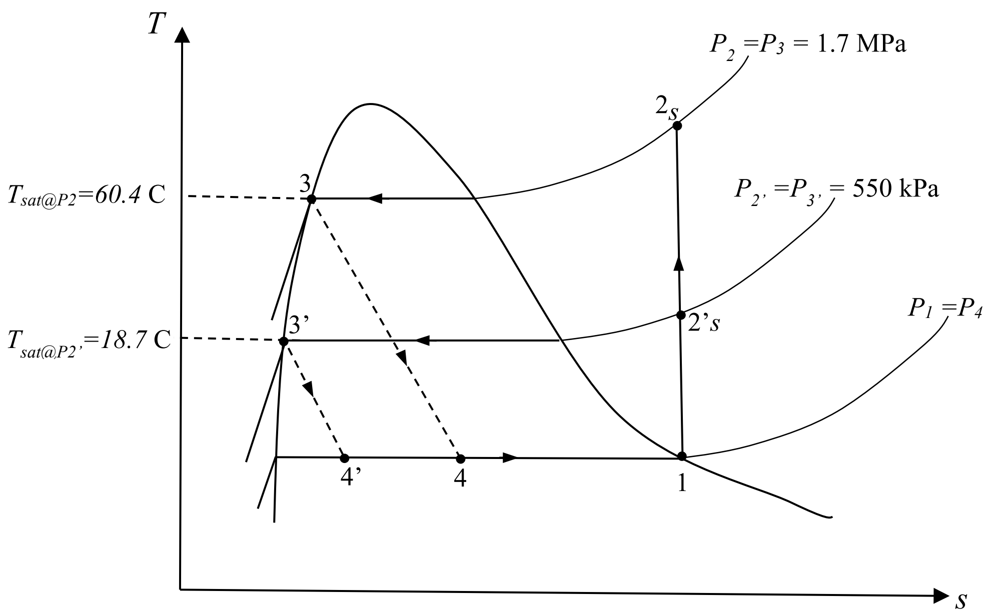
Approximations: The refrigerator operates on the ideal vapor compression cycle as shown in the schematic

Analysis: Take the condenser as the system.



Heat must flow from the refrigerant flowing through the condenser to the surrounding air for the refrigeration cycle to operate. Therefore, the saturation temperature at the operating pressure of the condenser must be greater than the kitchen air temperature.

Ideal vapor compression refrigeration cycles operating with condenser pressures of 1.7 MPa and 550 kPa are illustrated in the following *T-s* diagram.



Since heat transfer from the refrigerant flowing through the condenser to the ambient kitchen air is required for the cycle to operate, the temperature of the refrigerant in the condenser must be at approximately 10 degC above the kitchen air temperature. Assuming a typical kitchen air temperature of 27 C, the temperature of the refrigerant in the condenser must be 37 C or greater. The saturation temperature at 550 kPa is 18.7 C, which is below typical kitchen air temperatures. Therefore, the refrigerator will not work if the condenser is operated at 550 kPa.

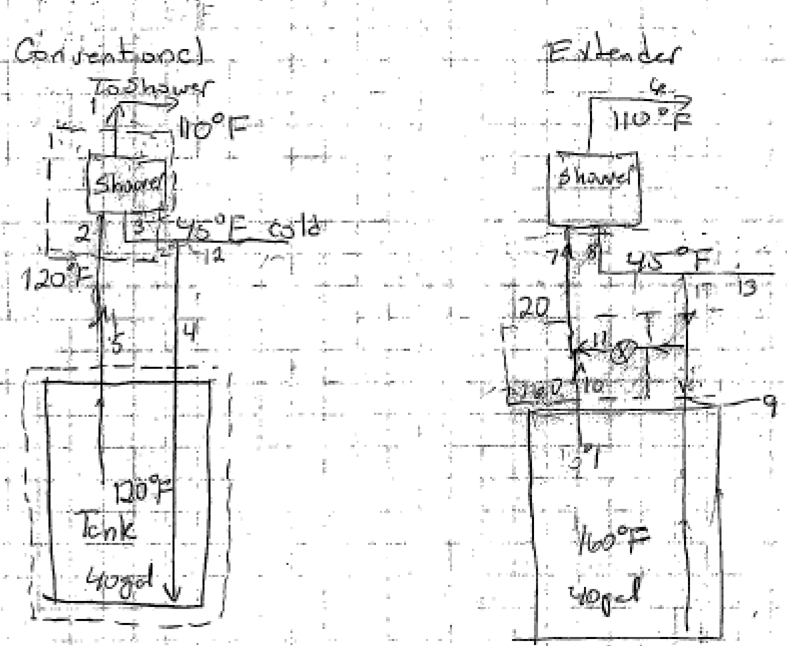
The advantages of operating the compressor at lower pressures can be seen by further analyzing the *T-s* process diagram. Operating the condenser at a lower pressure increases the cooling capacity. Note that the area under the 4'–1 curve is greater than the area under the 4–1 curve. The work input to the compressor is much less when the condenser is operated at 550 kPa (Compare the length of 1–2' with the length of 1–2). Therefore, operating the condenser at lower pressure increases COP_R. The saturation pressure of R-134a at 37 C is 938 kPa, so the minimum possible condenser pressure is approximately 940 kPa.

If operating the condenser at lower pressures increases COP_R as well as making the refrigerator safer and less expensive, why are condensers in typical household refrigerators operated at a higher pressure (~1.7 MPa)? Household appliances are generally designed to operate under *extreme* conditions rather than under *typical* conditions. Extreme operating conditions for a refrigerator would occur when the cooling system in a home fails and the kitchen air temperature increases to greater than 40 C. To operate under these extreme conditions, the temperature of the refrigerant in the condenser should be 50 – 60 C. Note that the saturation temperature of R-134a is 60 C at 1.7 MPa.

Recommendation: The temperature of the refrigerant in the condenser will be too low if it is operated at 550 kPa, so purchase of the refrigerator is not recommended.

2. Solution to problem 2

2. Compare the performance of a conventional water heater and a water heater with an "extender" on it



For Conventional - Water Heater

$$0 = \dot{m}_2 h_2 + \dot{m}_3 h_3 - \dot{m}_1 h_1 \quad 8.267 \frac{lbm}{gal}$$

$$\dot{m}_1 = \frac{2\,gal}{min}\left[\frac{1\,bm}{.01617\ ft^3}\ \frac{35.315\ ft^3}{264.17\ gal}\right] = 16.53 \frac{lbm}{min}$$

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \qquad \text{For water } h \approx C_p T$$

$$0 = \dot{m}_2 \cancel{C_p} T_2 + (\dot{m}_1 - \dot{m}_2)\cancel{C_p} T_3 - \dot{m}_1 \cancel{C_p} T_1$$

For small differences in "T" $C_p = \text{const.}$

$$-\dot{m}_2 T_2 + \dot{m}_2 T_3 = \dot{m}_1 T_3 - \dot{m}_1 T_1$$

$\dot{m}_2 (T_3 - T_2) = \dot{m}_1 (T_3 - T_1)$

$\dot{m}_2 = \dfrac{\dot{m}_1 (T_1 - T_3)}{T_2 - T_3} = 16.53 \dfrac{lbm}{hr} \dfrac{(110-45)}{120-45}$

$\dot{m}_2 = 14.326 \dfrac{lbm}{min}$

$\dot{V} = 14.326 \dfrac{lbm}{min} \cdot \dfrac{gal}{8.267\ lbm} = 1.732 \dfrac{gal}{min}$

$t = \dfrac{V}{\dot{V}} = \dfrac{40\ gal}{1.7328 \frac{gal}{min}} = \underline{23.08\ min}$

For "Extender"

$\dot{m}_7 = \dot{m}_2 \Rightarrow$ The shower requires the same flow rate at point "7" as point "2". But flow out of heat exchanger point "10" is different.

$0 = \dot{m}_{10} h_{10} + \dot{m}_{11} h_{11} - \dot{m}_7 h_7$

$\dot{m}_7 = \dot{m}_{10} + \dot{m}_{11}$

$h = C_p T$ for water

C_p is constant

$0 = \dot{m}_{10} \cancel{C_p} T_{10} + \dot{m}_{11} \cancel{C_p} T_{11} - \dot{m}_7 \cancel{C_p} T_7$

$0 = \dot{m}_{10} T_{10} + (\dot{m}_7 - \dot{m}_{10}) T_{11} - \dot{m}_7 T_7$

$-\dot{m}_{10} T_{10} + \dot{m}_{10} T_{11} = \dot{m}_7 T_{11} - \dot{m}_7 T_7$

$\dot{m}_{10} = \dfrac{\dot{m}_7 (T_{11} - T_7)}{(T_{11} - T_{10})} = 14.326 \dfrac{lbm}{min} \left(\dfrac{45-120}{45-160} \right)$

$\dot{m}_{10} = 9.343 \dfrac{lbm}{min}$

Extender Cont.

$$\dot{V} = 9.343 \frac{lbm}{min} \cdot \frac{gal}{8.267\ lbm} = 1.13 \frac{gal}{hr}$$

$$t_{ext} = \frac{40\ gal}{1.13 \frac{gal}{min}} = 35.4\ min.$$

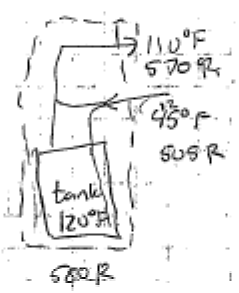
Comments: The extender can provide 12.3 minutes longer of hot water for the shower.

II. Entropy Analysis:

Conventional

$$\frac{dS_{cv}}{dt} = \dot{m}_i s_i - \dot{m}_e s_e + \frac{\dot{Q}_b}{T_b} + \dot{S}_{gen}$$

Considering the tanks before and after a shower including the piping and shower to find the total S_{gen} before and after



During the shower period $\dot{Q}_b$ is assumed negligible $\cancel{\frac{\dot{Q}_b}{T_b}} = 0$

$$\dot{S}_{gen} = \frac{dS_{cv}}{dt} + \dot{m}_e s_e - \dot{m}_i s_i$$

$$\int \frac{\delta S_{gen}}{\cancel{dt}} = \int \frac{dS_{cv}}{\cancel{dt}} + \int \frac{\delta m_e s_e}{\cancel{dt}} - \int \frac{\delta m_i}{\cancel{dt}} s_i$$

$$S_{gen\,1-2} = (S_2 - S_1)_{cv} + m_{e1-2} s_e - m_{i1-2} s_i$$

Entropy Analysis cont.

$S_{gen} = m_2 s_2 - m_1 s_1 + \dot{m}_{e1-2} s_e - \dot{m}_{i1-2} s_i \qquad m_{e1-2} = m_{i1-2}$

$= m_{tank}(s_2 - s_1)_{tank} + \dot{m}_{in1-2}(s_e - s_i) \qquad = \frac{2\,gal}{min} \cdot 8.267 \frac{lbm}{gal} = 16.534 \frac{lbm}{min}$

$m_{tank} = (40\,gal)(8.267 \frac{lbm}{gal}) = 330.68\,lbm$

$m_{in} = 16.534 \frac{lbm}{min} \cdot 23.08\,min = 381.6\,lbm$

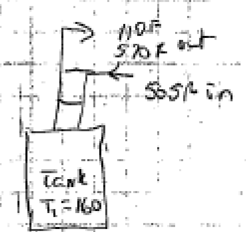
$S_{gen} = (330.68\,lbm)(C_p \ln T_2/T_1) + 381.6\,lbm\; C_p \ln(T_e/T_i)$

$= (330.68\,lbm)(0.1102 \frac{Btu}{lbm\,°R}) \ln\left(\frac{505}{580}\right) + (381.6\,lbm)(0.1102 \frac{Btu}{lbm\,°R}) \ln\left(\frac{580}{505}\right)$

$S_{gen} = -5.046 + 5.092 = \underline{0.0456} \frac{Btu}{R}$

Entropy w/ Extender.

The same equations apply but a different T_1 for the tank



$T_1 = 620\,R$
$T_2 = 505\,R$

$S_{gen} = m_{tank} C_p \ln\left(\frac{T_2}{T_1}\right) + m_{in} C_p \ln\left(T_e/T_i\right)$

$\dot{m}_{in} = \frac{2\,gal}{min}\; 8.627 \frac{lb}{gal} = 16.534\; lbm/min$

$m_{in} = (16.534\, lbm/min)(35.4\,min) = 585.3\; lbm$

$S_{gen} = (330.68\,lbm)(0.1102 \frac{Btu}{lbm\,°R}) \ln \frac{505}{620} + (585.3\,lbm)(0.1102 \frac{Btu}{lbm\,°R}) \ln\left(\frac{570}{505}\right)$

$S_{gen} = -7.4763 + 7.8095 = 0.333 \frac{Btu}{R}$

Summary:

- The tank extender increases the amount of shower time significantly, in this case by 53%
- The tank extender significantly increases entropy generation because the stored temperature is higher and mixes to a lower temperature
- The tank will lose more heat, almost doubling the temperature difference between the tank and 70°F room causing increased energy loss between showers
- The higher tank temperatures may impact corrosion and decrease tank life.

Sample Problems

S.1 Consider a large performing arts auditorium filled to capacity with 1000 people. The auditorium has a volume of 0.15 x 10^6 m^3. At rest, the human metabolism generates about 85 W per person. The air temperature in the auditorium is to be maintained at 20°C. Suggest a possible building code standard for the number of total air changes per hour in the auditorium if no more than 1 deg K rise in air temperature is allowed. Clearly state any assumptions used in your analysis.

Explain how you would size the air conditioning system for the auditorium.

Suppose the air conditioning system fails. How hot will the auditorium get after a two-hour performance?

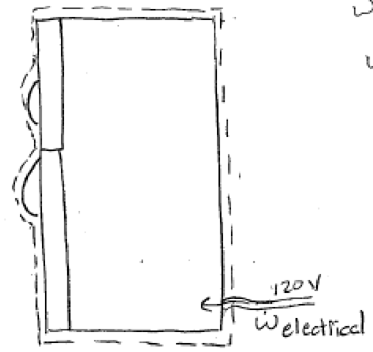
S.2 Following recommended industry practices, restaurants serve hot beverages at temperatures exceeding 80 C, and consumers typically ingest these beverages at a temperature of at least 60 C. Estimate the amount of entropy generated when a person drinks a hot beverage. Estimate the amount of entropy generated when a person drinks a cold beverage (the recommend temperature range for chilled beverages is 3 – 5 C). Based on the results of your analysis, what conclusion can you draw regarding counsel given in the Word of Wisdom to abstain from hot drinks? (See D&C 89:9)

S.3 1. An undergraduate engineering student selected a refrigerator as a real-world device to analyze for a class project. Look over the results presented by the students and produce a critical assessment of their work.

1. Identify errors in the student has made in their application of the energy equation and approach that leads to their “efficiency” of a refrigerator.

2. Using a thermometer, clock, and a watt meter, suggest a plan for “measuring” as best you can, the COP_R of a household refrigerator full of food.

Students Work:



During a transient period from when the refrigerator turns on to when it turns of the air inside cools down.

The energy equation is

Assume $\dot{Q}=0$

$$\frac{dU}{dt} = \dot{W}_{el,in} + \cancel{\dot{Q}_{in}}$$

$$mc_v \Delta T = \dot{W}_{el} \Delta t$$

The efficiency of the refrigerator is

$$\eta = \frac{\text{Cooling Energy}}{\text{Electrical Energy}}$$

$$\eta = \frac{mc_v \Delta T}{\dot{W}_{el} \Delta t}$$

I measured: 600 Watts for 3 min

The air temp. changed from

$T_1 = 50°F$ to $T_2 = 34°F$

The refrigerator is $54 ft^3$

Calculations:

$$m = \frac{PV}{RT} = \frac{(101. kPa)(54 ft^3)}{(8.314)(278 K)} \frac{0.0283 m^3}{ft^3}$$

$$m = 0.0668 \text{ kg}$$

$$c_v = 0.718 \text{ kJ/kg K}$$

$$\eta = \frac{(0.0668 kg)(0.718)(16/1.8) °C}{(600 \frac{J}{s})(3 min) \frac{60 s}{min}}$$

$$\eta = \frac{0.426 \text{ kJ}}{108.0 \text{ kJ}} = 0.39\%$$

Conclusion:
My refrigerator is very inefficient