

# ChE-304 Problem Set 2

Week 2

## Problem 1

Should I heat my house with a Carnot heat pump or an electric heater? Electric heaters are very efficient. ~100% of the electrical work ends up as heat in the house.

I would like to heat my house to  $24^{\circ}\text{C}$  and the temperature outside in the winter is, on average  $-4^{\circ}\text{C}$ .

**Problem 2**

Let's calculate the efficiency of a typical refrigerator/freezer in your home. A typical refrigeration fluid is tetrafluoroethane (R134a). The evaporator usually runs at atmospheric pressure and R134a boils at  $-26^{\circ}\text{C}$ . Even on hot summer days, which can reach on average  $29^{\circ}\text{C}$  in Switzerland, the refrigerator condenser fluid should always remain at least  $10^{\circ}\text{C}$  hotter than the environment.

Assume there is 1 kg of refrigerant. You can also assume that all the work given by the compressor is converted to enthalpy in the fluid. Finally, assume that the expansion valve is an isentropic process. Use the data in the annex.

**What is the efficiency?**

**Assuming that a refrigerator uses about 500 Watt, what is its cooling power and how does that compare to a Carnot refrigerator?**

*Hint: look at figure 1.12. Find the data points on the graph at which we need to determine the properties. You can find out these properties by what you know about the Rankine cycle.*

**Annex: Saturation properties** Data pulled for 1,1,1,2-tetrafluoro-Ethane, (R134a) from:

<http://webbook.nist.gov/>

## Liquid Phase Data

### Data on Saturation Curve

| Temperature<br>(C) | Pressure<br>(atm) | Density<br>(mol/l) | Volume<br>(l/mol) | Internal<br>Energy<br>(kJ/kg) | Enthalpy<br>(kJ/kg) | Entropy<br>(J/g*K) | Cv<br>(J/g*K) | Cp<br>(J/g*K) | Sound<br>Spd.<br>(m/s) | Joule-<br>Thomson<br>(F/atm) | Viscosity<br>(uPa*s) | Therm.<br>Cond.<br>(W/m*K) | Surf.<br>Tension<br>(N/m) | Phase  |
|--------------------|-------------------|--------------------|-------------------|-------------------------------|---------------------|--------------------|---------------|---------------|------------------------|------------------------------|----------------------|----------------------------|---------------------------|--------|
| -31.000            | 0.79392           | 13.637             | 0.073332          | 159.46                        | 159.52              | 0.84339            | 0.84264       | 1.2710        | 764.94                 | -0.049807                    | 406.92               | 0.10624                    | 0.016194                  | liquid |
| -26.000            | 1.0034            | 13.490             | 0.074127          | 165.83                        | 165.90              | 0.86943            | 0.84825       | 1.2807        | 741.63                 | -0.047421                    | 378.30               | 0.10387                    | 0.015425                  | liquid |
| -21.000            | 1.2543            | 13.342             | 0.074951          | 172.25                        | 172.34              | 0.89514            | 0.85396       | 1.2909        | 718.42                 | -0.044825                    | 352.46               | 0.10153                    | 0.014664                  | liquid |
| -16.000            | 1.5522            | 13.191             | 0.075807          | 178.72                        | 178.83              | 0.92054            | 0.85977       | 1.3017        | 695.29                 | -0.041991                    | 329.00               | 0.099225                   | 0.013912                  | liquid |
| -11.000            | 1.9028            | 13.038             | 0.076699          | 185.24                        | 185.38              | 0.94566            | 0.86569       | 1.3132        | 672.24                 | -0.038887                    | 307.61               | 0.096944                   | 0.013167                  | liquid |
| -6.0000            | 2.3121            | 12.882             | 0.077630          | 191.81                        | 191.99              | 0.97051            | 0.87171       | 1.3254        | 649.22                 | -0.035475                    | 288.00               | 0.094689                   | 0.012431                  | liquid |
| -1.0000            | 2.7865            | 12.722             | 0.078603          | 198.44                        | 198.66              | 0.99511            | 0.87785       | 1.3383        | 626.24                 | -0.031707                    | 269.96               | 0.092457                   | 0.011704                  | liquid |
| 4.0000             | 3.3325            | 12.559             | 0.079623          | 205.13                        | 205.40              | 1.0195             | 0.88410       | 1.3523        | 603.27                 | -0.027530                    | 253.29               | 0.090246                   | 0.010986                  | liquid |
| 9.0000             | 3.9569            | 12.392             | 0.080695          | 211.89                        | 212.21              | 1.0437             | 0.89048       | 1.3672        | 580.29                 | -0.022877                    | 237.83               | 0.088054                   | 0.010278                  | liquid |
| 14.000             | 4.6670            | 12.221             | 0.081825          | 218.71                        | 219.09              | 1.0677             | 0.89700       | 1.3835        | 557.28                 | -0.017667                    | 223.42               | 0.085878                   | 0.0095797                 | liquid |
| 19.000             | 5.4699            | 12.045             | 0.083021          | 225.61                        | 226.06              | 1.0915             | 0.90366       | 1.4011        | 534.23                 | -0.011801                    | 209.96               | 0.083715                   | 0.0088918                 | liquid |
| 24.000             | 6.3734            | 11.864             | 0.084290          | 232.59                        | 233.12              | 1.1152             | 0.91048       | 1.4205        | 511.10                 | -0.0051558                   | 197.32               | 0.081564                   | 0.0082146                 | liquid |
| 29.000             | 7.3852            | 11.676             | 0.085643          | 239.65                        | 240.28              | 1.1388             | 0.91748       | 1.4419        | 487.90                 | 0.0024230                    | 185.42               | 0.079420                   | 0.0075488                 | liquid |
| 34.000             | 8.5135            | 11.482             | 0.087091          | 246.80                        | 247.54              | 1.1623             | 0.92468       | 1.4658        | 464.58                 | 0.011131                     | 174.18               | 0.077281                   | 0.0068949                 | liquid |
| 39.000             | 9.7666            | 11.280             | 0.088649          | 254.06                        | 254.92              | 1.1858             | 0.93212       | 1.4926        | 441.13                 | 0.021221                     | 163.52               | 0.075143                   | 0.0062535                 | liquid |
| 44.000             | 11.153            | 11.070             | 0.090336          | 261.42                        | 262.43              | 1.2092             | 0.93981       | 1.5232        | 417.53                 | 0.033025                     | 153.37               | 0.073003                   | 0.0056255                 | liquid |
| 49.000             | 12.683            | 10.849             | 0.092174          | 268.91                        | 270.07              | 1.2327             | 0.94781       | 1.5584        | 393.74                 | 0.046984                     | 143.66               | 0.070857                   | 0.0050116                 | liquid |

## Vapor Phase Data

### Data on Saturation Curve

| Temperature<br>(C) | Pressure<br>(atm) | Density<br>(mol/l) | Volume<br>(l/mol) | Internal<br>Energy<br>(kJ/kg) | Enthalpy<br>(kJ/kg) | Entropy<br>(J/g*K) | Cv<br>(J/g*K) | Cp<br>(J/g*K) | Sound<br>Spd.<br>(m/s) | Joule-<br>Thomson<br>(F/atm) | Viscosity<br>(uPa*s) | Therm.<br>Cond.<br>(W/m*K) | Phase |
|--------------------|-------------------|--------------------|-------------------|-------------------------------|---------------------|--------------------|---------------|---------------|------------------------|------------------------------|----------------------|----------------------------|-------|
| -31.000            | 0.79392           | 0.041473           | 24.112            | 360.68                        | 379.69              | 1.7526             | 0.67550       | 0.77755       | 145.04                 | 9.0236                       | 9.5996               | 0.0089085                  | vapor |
| -26.000            | 1.0034            | 0.051698           | 19.343            | 363.55                        | 382.82              | 1.7471             | 0.68859       | 0.79444       | 145.67                 | 8.3821                       | 9.7818               | 0.0093196                  | vapor |
| -21.000            | 1.2543            | 0.063820           | 15.669            | 366.42                        | 385.94              | 1.7422             | 0.70194       | 0.81215       | 146.19                 | 7.8137                       | 9.9633               | 0.0097333                  | vapor |
| -16.000            | 1.5522            | 0.078086           | 12.806            | 369.28                        | 389.02              | 1.7379             | 0.71555       | 0.83075       | 146.59                 | 7.3070                       | 10.144               | 0.010150                   | vapor |
| -11.000            | 1.9028            | 0.094762           | 10.553            | 372.12                        | 392.06              | 1.7341             | 0.72941       | 0.85031       | 146.85                 | 6.8534                       | 10.325               | 0.010571                   | vapor |
| -6.0000            | 2.3121            | 0.11414            | 8.7612            | 374.95                        | 395.06              | 1.7307             | 0.74354       | 0.87094       | 146.98                 | 6.4458                       | 10.507               | 0.010996                   | vapor |
| -1.0000            | 2.7865            | 0.13654            | 7.3241            | 377.75                        | 398.02              | 1.7276             | 0.75792       | 0.89272       | 146.96                 | 6.0788                       | 10.689               | 0.011427                   | vapor |
| 4.0000             | 3.3325            | 0.16231            | 6.1612            | 380.53                        | 400.92              | 1.7250             | 0.77254       | 0.91581       | 146.79                 | 5.7479                       | 10.874               | 0.011865                   | vapor |
| 9.0000             | 3.9569            | 0.19183            | 5.2128            | 383.27                        | 403.76              | 1.7226             | 0.78742       | 0.94036       | 146.47                 | 5.4491                       | 11.061               | 0.012312                   | vapor |
| 14.000             | 4.6670            | 0.22556            | 4.4334            | 385.98                        | 406.53              | 1.7204             | 0.80254       | 0.96659       | 145.97                 | 5.1794                       | 11.252               | 0.012769                   | vapor |
| 19.000             | 5.4699            | 0.26398            | 3.7882            | 388.64                        | 409.22              | 1.7184             | 0.81792       | 0.99476       | 145.31                 | 4.9360                       | 11.448               | 0.013239                   | vapor |
| 24.000             | 6.3734            | 0.30764            | 3.2506            | 391.25                        | 411.82              | 1.7166             | 0.83357       | 1.0252        | 144.45                 | 4.7166                       | 11.651               | 0.013725                   | vapor |
| 29.000             | 7.3852            | 0.35720            | 2.7996            | 393.80                        | 414.33              | 1.7148             | 0.84951       | 1.0585        | 143.40                 | 4.5193                       | 11.863               | 0.014232                   | vapor |
| 34.000             | 8.5135            | 0.41340            | 2.4190            | 396.27                        | 416.72              | 1.7131             | 0.86577       | 1.0950        | 142.14                 | 4.3422                       | 12.086               | 0.014764                   | vapor |
| 39.000             | 9.7666            | 0.47713            | 2.0958            | 398.66                        | 418.99              | 1.7114             | 0.88238       | 1.1358        | 140.66                 | 4.1839                       | 12.323               | 0.015329                   | vapor |
| 44.000             | 11.153            | 0.54948            | 1.8199            | 400.96                        | 421.11              | 1.7096             | 0.89941       | 1.1818        | 138.95                 | 4.0430                       | 12.579               | 0.015935                   | vapor |
| 49.000             | 12.683            | 0.63174            | 1.5829            | 403.13                        | 423.07              | 1.7077             | 0.91692       | 1.2345        | 136.98                 | 3.9184                       | 12.858               | 0.016595                   | vapor |

## Isobaric Data for P = 9.7660 atm

| Temperature<br>(C) | Pressure<br>(atm) | Density<br>(mol/l) | Volume<br>(l/mol) | Internal<br>Energy<br>(kJ/kg) | Enthalpy<br>(kJ/kg) | Entropy<br>(J/g*K) | Cv<br>(J/g*K) | Cp<br>(J/g*K) | Sound<br>Spd.<br>(m/s) | Joule-<br>Thomson<br>(F/atm) | Viscosity<br>(uPa*s) | Therm.<br>Cond.<br>(W/m*K) | Phase  |
|--------------------|-------------------|--------------------|-------------------|-------------------------------|---------------------|--------------------|---------------|---------------|------------------------|------------------------------|----------------------|----------------------------|--------|
| 20.000             | 9.7660            | 12.032             | 0.083113          | 226.70                        | 227.50              | 1.0952             | 0.90475       | 1.4007        | 534.10                 | -0.011844                    | 208.89               | 0.083603                   | liquid |
| 25.000             | 9.7660            | 11.846             | 0.084417          | 233.74                        | 234.56              | 1.1191             | 0.91161       | 1.4208        | 510.20                 | -0.0049433                   | 196.08               | 0.081397                   | liquid |
| 30.000             | 9.7660            | 11.653             | 0.085818          | 240.88                        | 241.72              | 1.1429             | 0.91869       | 1.4434        | 485.95                 | 0.0030563                    | 183.95               | 0.079181                   | liquid |
| 35.000             | 9.7660            | 11.450             | 0.087336          | 248.15                        | 249.00              | 1.1667             | 0.92603       | 1.4691        | 461.27                 | 0.012445                     | 172.40               | 0.076949                   | liquid |
| 38.998             | 9.7660            | 11.280             | 0.088649          | 254.06                        | 254.92              | 1.1858             | 0.93211       | 1.4926        | 441.14                 | 0.021216                     | 163.52               | 0.075144                   | liquid |
| 38.998             | 9.7660            | 0.47710            | 2.0960            | 398.66                        | 418.99              | 1.7114             | 0.88237       | 1.1358        | 140.66                 | 4.1840                       | 12.323               | 0.015328                   | vapor  |
| 40.000             | 9.7660            | 0.47367            | 2.1112            | 399.65                        | 420.13              | 1.7150             | 0.88028       | 1.1276        | 141.31                 | 4.1135                       | 12.367               | 0.015388                   | vapor  |
| 45.000             | 9.7660            | 0.45786            | 2.1841            | 404.50                        | 425.68              | 1.7326             | 0.87329       | 1.0960        | 144.36                 | 3.7963                       | 12.586               | 0.015702                   | vapor  |
| 50.000             | 9.7660            | 0.44379            | 2.2533            | 409.25                        | 431.10              | 1.7495             | 0.87043       | 1.0749        | 147.18                 | 3.5254                       | 12.803               | 0.016035                   | vapor  |
| 55.000             | 9.7660            | 0.43110            | 2.3196            | 413.94                        | 436.44              | 1.7659             | 0.87025       | 1.0606        | 149.82                 | 3.2900                       | 13.017               | 0.016381                   | vapor  |
| 60.000             | 9.7660            | 0.41953            | 2.3836            | 418.60                        | 441.72              | 1.7819             | 0.87187       | 1.0509        | 152.30                 | 3.0827                       | 13.229               | 0.016737                   | vapor  |

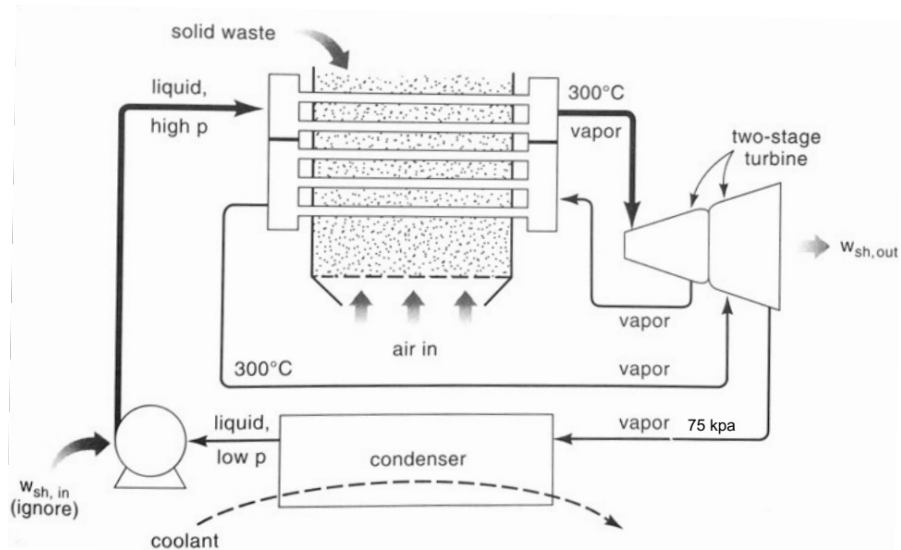
**Problem 3**

Let's try to calculate the Carnot efficiency of a gasoline engine by assuming that upon combustion all the higher heating value of the gas is used to heat the resulting product gases at constant volume.

Assume gasoline is pure octane ( $C_8H_{18}$ ,  $M_w = 114$ ), that air is 20%  $O_2$  80%  $N_2$  and that the amount of air needed is stoichiometric. You can assume that product gases are ideal gas and that their CV is  $0.8 \text{ KJ/(kg K)}$ .

#### Problem 4

Imagine a power plant designed to burn EPFL's garbage. The temperature in the boiler cannot go higher than  $300^{\circ}\text{C}$ . The condenser can operate slightly below atmospheric pressure at 75 kPa. The working fluid is water, and because EPFL engineers are smart, they added a reheating cycle such that the setup looks like the following:



Can you calculate the efficiency? You will need steam tables, which you can find here: <https://webbook.nist.gov/chemistry/fluid/>

How does it compare to the Carnot efficiency?