Thermodynamics and Statistical Physics

Part I – Thermodynamics

Exam T2

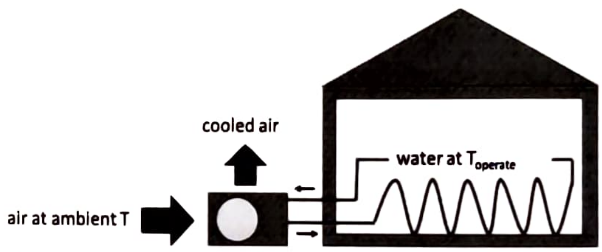
Wednesday, November 11 2021, 8:30-11:30, Aletta Jacobshal

The total number of points that can be reached in this exam is 90.

Final grade = (points/10) + 1.

1) **Heat pump (30p)**

An important part of our personal CO_2 emission footprint is due to heating of residential houses that is based on fossile fuels. CO_2-reduction scan be accomplished by replacing conventional heating systems with heat pumps. The figure shows the example of an air-water heatpump, where a thermodynamic cycle extracts heat from ambient air and deposits heat into the water-filled floor heating system inside the house using electrical energy. Assume that the heat pump is a reversible thermodynamical cycle based on the Carnot process. The air outside and the water of the floor-heating system are the two reservoirs.



a) The efficiency of a heat pump is called "coefficient of performance" (COP). Give the general definition for the COP of a heat pump. **(6 pt)**

b) Calculate COPs for for the heatpump with a water temperature T_{water} of 40°C (low temperature floor heating) and for outside air temperatures of T_{air}=-10°C, 0°C and +10°C. Repeat the calculations for T_{water}=70°C (conventional high temperature radiators). Make a table. (hint: you need the efficiency of the Carnot cycle for this). Discuss the table in terms of realistic suitability of heat pumps for reduction of CO_2 emission. **(8 pt)**

c) Draw a P-V diagram of the thermodynamic cycle and indicate in which steps heat and work are exchanged with the environment. **(8 pt)**

d) Calculate the entropy change inside and outside the house that is occuring for 1 kWh of electrical energy going into the heat pump as work (assume T_{air}=0°C and T_{air}=40°C). **(8 pt)**

2) **Heat transport (30p)**

Assume Your apartment had a very old window of area $A = 2$ m² with thermal conductance $\frac{\kappa}{L}$ $= 6$ Wm^{-2}K^{-1}. To save energy, this window is replaced by a state of the art double-pane window with $\frac{\kappa}{L} = 1$ Wm^{-2}K^{-1}.

a) Use the thermal diffusion equation in one dimension

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2}$$

To determine a functional form of the temperature profile through the window $T(x)$, with the temperatures T_{outside} and T_{inside} both constant. **(8 pt)**

b) Give a functional form for the heat flux through the window using $T(x)$. **(8 pt)**
c) How much energy do you save per winter day (24 hours), assuming a constant temperature outside of -5 °C and inside of 20 °C? **(8 pt)**
d) In standard double-pane windows, the volume between the two glass panes is filled with air (mostly $^{14}N_2$). The thermal conductance can be lowered even more, by filling this volume with ^{40}Ar. Why is the thermal conductance lower for ^{40}Ar? Give two reasons. **(6 pt)**

3) **Spontaneous? (8 pt)**

Give two examples for processes occurring spontaneously and two examples for processes occuring non-spontaneously. (Do not simply reverse a given process to have spontaneous and non-spontaneous, I want 4 different processes!)

4) **Entropy (7 pt)**

Apply your knowledge of entropy to explain why heat flows from hot to cold.

5) **Isothermal Expansion (15pt)**

Consider a piston filled with 1 l of Ar at T=273.15 K and p=1×10^5 Pa. The gas can be considered an ideal gas.

a) The gas in the piston expands isothermally against a constant external pressure of p=2×10^5 Pa. Determine the change in internal energy, the work done by the gas and the heat flow. **(5pt)**
b) Repeat the calculation for a reversible isothermal expansion. Why is there a difference in work between a) and b)? **(10pt)**

Constants:

Avogardro's number:	N_A=6.02 10^{23} mol^{-1}
Boltzmann constant:	k_B=1.381 10^{-23} J\K
Gas constant:	R=8.31 JK^{-1}mol^{-1}
Atomic mass unit (u):	m_u=1.67 10^{-27} kg
Electronvolt:	1 eV=1.6 10^{-19} J