Examination Thermal Energy Storage (4P730)

Date: 19 January 2011
Time: 14:00 – 17:00

The exam consists of 4 problems.

Please note on every sheet of paper you use the following:

1. The problem number
2. Your last name and initials
3. Your identity (student) number
4. Your department

The use of course books and notes is <u>not</u> allowed.
The use of simple calculators is allowed.

Additional formulas and graphs on heat storage and heat transfer can be found at the end of the exam text.

Good luck!

Problem 1 Water vessel heat loss

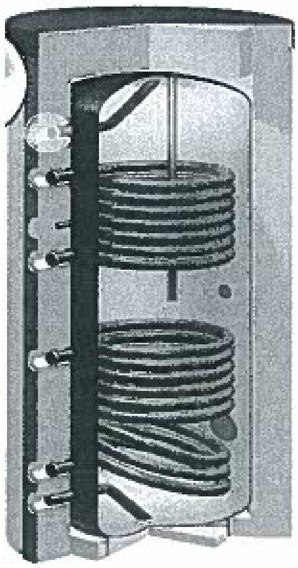
All sub questions can be made independently.

a) What are critical issues in the heat loss of solar water tanks? Mention at least 2 typical problems found in real solar water tanks and explain what goes wrong.

b) Calculate the heat loss in W/K through the top, the bottom and the wall of a well insulated cylindrical water vessel, assuming a homogeneous vessel temperature of 60 °C, a tank diameter of 60 cm, a tank height of 80 cm, an insulation thickness of 5 cm, an insulation conductivity of 0,07 W/mK and an ambient temperature of 20 °C (both for the air and the walls). **Assume that the thermal resistance through the insulation is dominant (ignore the other resistances). Ignore the thermal capacity of the insulation.** See last page for additional information on the formulas.

c) For the problem in b), calculate the time required for the vessel to cool down to 30 °C, assuming that the vessel continues to be fully mixed throughout the cooling down process. If you could not solve 2b), then assume for this calculation a total heat loss for the vessel of 2 W/K. You may use Cp_{water}=4200 J/kgK and ρ_{water}=1000 kg/m^3.

d) Is the assumption realistic that the vessel will remain fully mixed during the cooling down process? Explain.



Problem 2 PCM

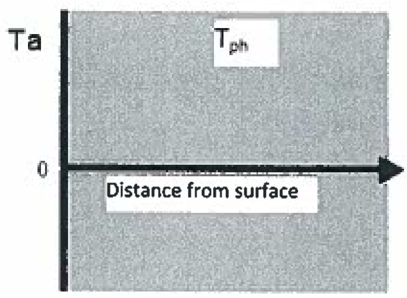
All sub questions can be made independently.

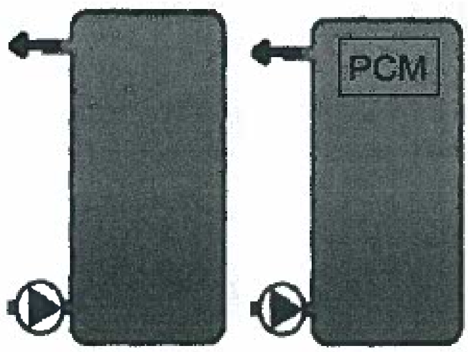
a) Explain the use of gelling agents in PCM's. For what class of PCM would these be required?

b) Derive the equation for the specific power (in W/m^2) transferred to a melting layer of PCM as a function of time, assuming as initial state a solid layer of PCM at a fixed melting temperature Tph for the PCM immersed in a large bath with a fixed temperature Ta, and assuming that the external heat transfer is high and that convection in the molten PCM can be ignored. The PCM has a melting enthalpy DH (in J/kg). See figure below left.

c) What methods are available to increase the conductivity of a layer of PCM? Assume that the heat transfer of a PCM can be improved from k=0.2 W/mK to k=20 W/mK. How much would this change the time required to melt a layer of this PCM? Explain.

d) Two water vessels with a diameter 50 cm and a height 50 cm are discharged at a rate of 6 l/min from the top segment, with cold water of 10 C flowing in at the bottom. Both vessels have an initial temperature of 70 °C and are stratified into 8 segments. One vessel is entirely filled with water (cp=4200 J/kg/K, density = 1000 kg/m^3). The other vessel has a plate of PCM in its highest segment, filling almost the entire segment (thickness 6 cm, diameter 45 cm, DH=200 kJ/kg, k=0,2 W/mK, density = 850 kg/m^3, melting temperature 50 °C, Cp=2000 J/kgK). The configuration is presented in the figure below right. Show in a figure the outflow temperature of both vessels over time and indicate the effects of the PCM. Take into account both the power and the energy content of the tanks and the PCM.

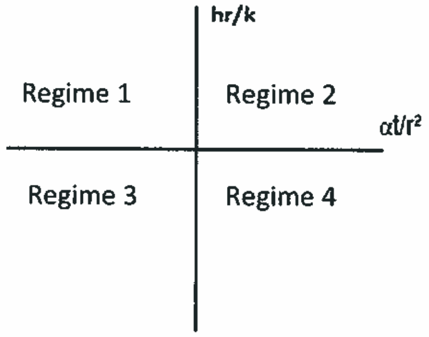




Problem 3 Solid

All sub questions can be made independently.

a) Indicate and explain the typical characteristics of the four regimes for heat storage in solids, as indicated schematically below, with respect to the temperature within the solid.



good internal ht, Bi is small

b) Calculate the amount of heat that can be stored per unit area in a concrete plate with a thickness of 20 cm, if heated up from 20 °C to 200 °C.

c) A concrete plate of 10 °C and 20 cm thickness is suddenly immersed into a 60 °C water flow. Assume h is large. Calculate the time required for the temperature at 1cm into the plate to reach 30 C. See last page for additional information on the formulas and graphs.

d) Same case as above, but now assume h=50 W/m^{2}K. Calculate the time required for the temperature at 8 cm into the plate to reach 50 °C. See last page for additional information on the formulas and graphs.

e) Explain in words the effect of the Biot number on the temperature development as shown in the two figures for the plate temperature distribution on the last page.

Additional information that may be relevant to this problem:

	heat capacity	density	conductivity	Thermal diffusivity
	J/kgK	kg/m3	W/mK	m2/s
water	4200	1000	0,6	1,43E-07
ice	2200	917	2,1	1,04E-06
olive oil	1650	920	0,2	1,12E-07
marble	750	2700	0,2	1,09E-07
concrete	920	2400	1,7	7,70E-07
glass	840	2600	0,9	4,26E-07
sand (dry)	800	1600	1,0	7,81E-07
copper	390	8900	390,0	1,12E-04
iron	460	7900	75,0	2,06E-05
lead	130	11300	35,0	2,38E-05
stainless steel	460	7800	50,0	1,39E-05

Problem 4 TCM

All sub questions can be made independently.

A heat storage is based on the reversible reaction $MgCl_2x2H_2O(s)+2H_2O(g) \Leftrightarrow MgCl_2x4H_2O(s)$ in an evacuated setup. Additional information that may be relevant to this problem is displayed in the table below. Assume that enthalpy and entropy values under standard conditions may be used for the calculation, and high temperature corrections may be ignored. See last page for additional information on the formulas.

a) Calculate the energy stored in the reaction above per kg of $MgCl_2x4H_2O$.

b) Calculate the equilibrium temperature for the reaction under standard conditions.

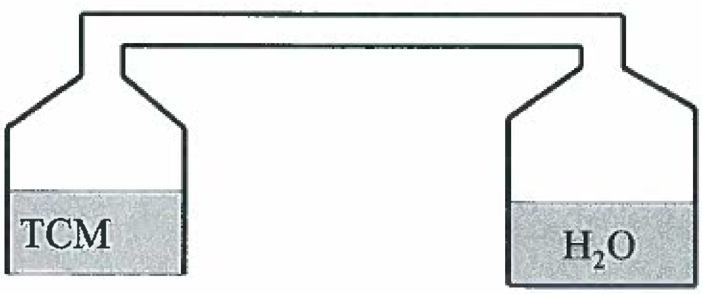
c) Calculate the equilibrium vapour pressure for the evaporation of water at 15 °C.

d) For the configuration shown in the figure below, calculate the temperature step between evaporator and sorbent bed, assuming that on discharge of the storage the H_2O is evaporated at 15 °C and that no pressure drop occurs within the system. (If you could not solve the previous question, assume that the water vapour equilibrium pressure at 15 °C is 20 mbar).

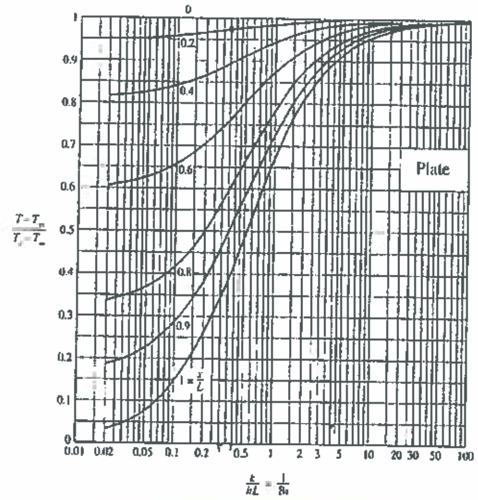
e) Calculate the difference between charging equilibrium temperature and discharging equilibrium temperature in the sorbent bed, for the case in which the evaporator is at 15°C, and 2 mbar pressure drop occurs in the vapour circuit of the system, both for charging and for discharging.

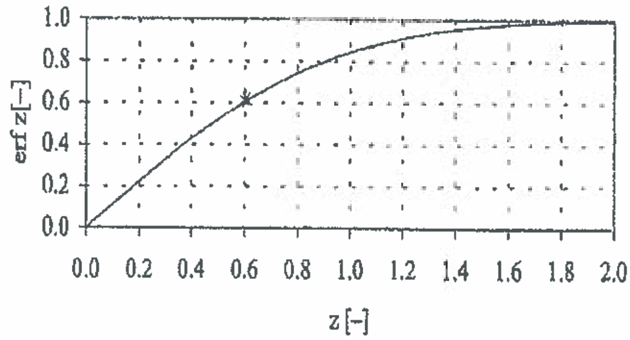
Table 93:Mg — MAGNESIUM (Prepared 1967) — Table 93:Mg

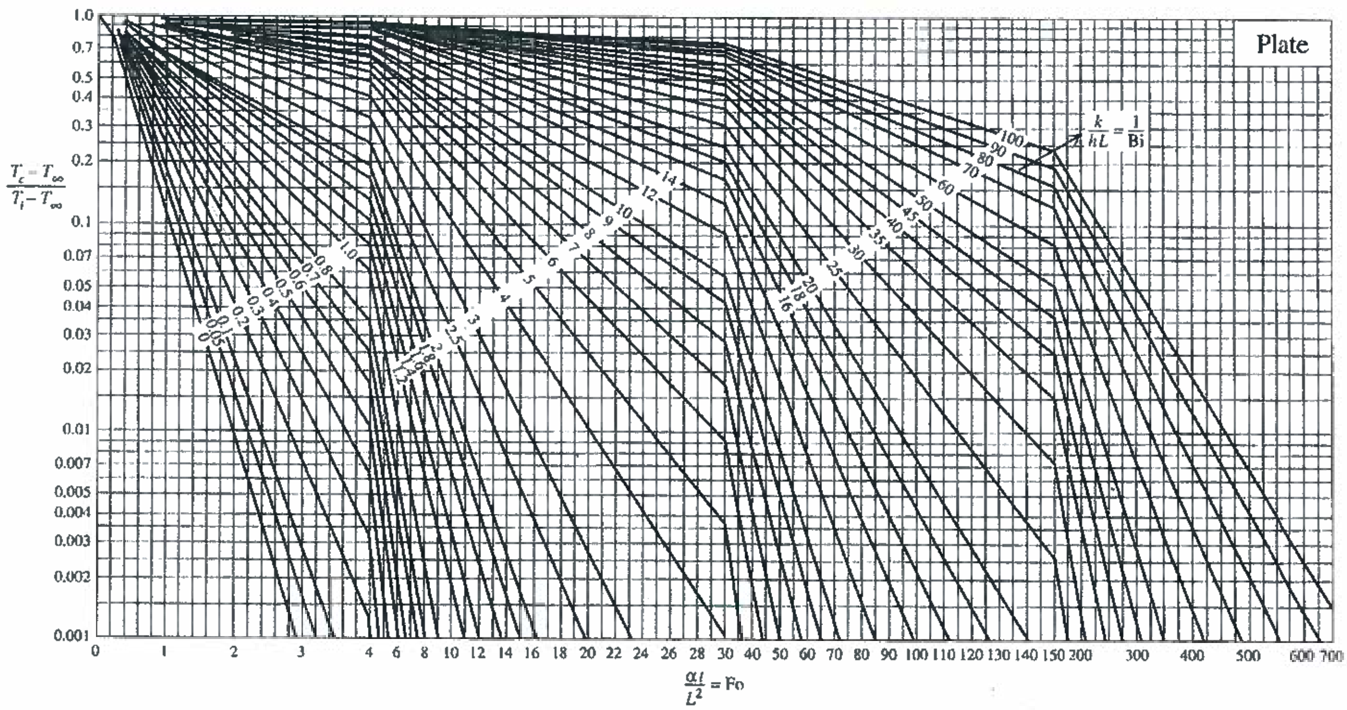
Substance Formula and Description	State	Molar mass g mol⁻¹	0 K: $\Delta_f H^\circ_0$ kJ mol⁻¹	298.15 K (25°C) and 0.1 MPa (1 bar): $\Delta_f H^\circ$ kJ mol⁻¹	$\Delta_f G^\circ$ kJ mol⁻¹	$H^\circ - H^\circ_0$ kJ mol⁻¹	S° J mol⁻¹ K⁻¹	C_p J mol⁻¹ K⁻¹
$MgCl_2$	g	95.2180	—	-400.4	—	—	—	—
	ai	95.2180	—	-801.15	-717.1	—	-25.1	—
$MgCl_2 \cdot H_2O$	cr	113.2334	—	-966.63	-861.74	—	137.2	115.27
$MgCl_2 \cdot 2H_2O$	cr	131.2488	—	-1279.72	-1118.00	—	179.9	159.20
$MgCl_2 \cdot 4H_2O$	cr	167.2796	—	-1898.99	-1623.29	—	264.0	241.42
$MgCl_2 \cdot 6H_2O$	cr	203.3104	—	-2499.02	-2114.64	—	366.1	315.06
H_2O	l	18.0154	—	-285.830	-237.129	13.293	69.91	75.291
	g	18.0154	-238.915	-241.818	-228.572	9.902	188.825	33.577
H_2	g	2.0160	0	0	0	8.468	130.684	28.824
Mg	cr	24.3120	0	0	0	5.000	32.68	24.89
	g	24.3120	146.499	147.70	113.10	6.197	148.650	20.786



Additional formulas and graphs on heat storage and heat transfer







$$\frac{T(t,x)-T_\infty}{T_0-T_\infty}=erf\left[\frac{x}{\sqrt{4\alpha t}}\right] \quad \text{for } t \ll L^2/\alpha$$

$$R_t=\frac{1}{h_e A_e}+\frac{\ln(R_o/R_i)}{2\pi k L}+\frac{1}{h_i A_i}$$

For reaction A(s) => B(s) + n×C(g):

$$\Delta H_{reaction}/n - T\,\Delta S_{reaction}/n + RT\ln p = \Delta G_{reaction}/n$$

For equilibrium: $\Delta G_{reaction}$=0.

R=8,31 J/mol/K