University of New Mexico
Mechanical engineering
Fall 2015 Ph.D. qualifying examination

Heat Transfer

Notes

- Time allowed: 150 minutes.
- Closed book / Closed Notes (one 8.5 × 11.00 in. sheet of formulas is allowed).
- Calculators are allowed.
- Laptops, cell phones, and similar electronic devices are not allowed.

Part 1: General knowledge (25 points)

1. A major assumption of the lumped capacitance method is . . .

   (a) The temperature of the solid body is spatially uniform
   (b) Heat is only transferred to the body by radiation
   (c) The body is spherical

   Answer:

2. A Biot number relates . . .

   (a) The relative importance of surface tension and inertia
   (b) Thermal conductivity and surface convective heat transfer
   (c) Convective and diffusive heat transfer in the medium

   Answer:

3. Heat flows from one body to another when they have different...

   (a) heat content
   (b) temperature
   (c) specific heat

   Answer:

4. The fundamental difference between convection processes in tube flow and in external flow is that:

   (a) In external flow, heat is always removed at a greater rate.
   (b) In external flow, there is an infinite (for all practical purposes) supply of fluid at constant temperature, while in tube flow the bulk temperature of the fluid is affected by the convective process.
   (c) in tube flow, the Nusselt number is constant, in external flow it is not.

   Answer:

5. In a series solution of a transient conduction problem, a Fourier number approaching infinity is mathematically consistent with:

   (a) Initial conditions.
   (b) Steady-state conditions.
   (c) Convection conditions.

   Answer:

6. In a series solution of a transient conduction problem, a one-term series solution is accurate if the Fourier number is large, because:

   (a) Low-frequency terms in the series have already decayed.

   (b) High-frequency terms in the series have already decayed.

   (c) Steady-state conditions are reached.

   Answer:

7. Arrays of vertical fins are used to remove heat from devices such as electronic equipment. For vertical fins in natural convection, there exists an optimum fin spacing, which represents the best compromise between:

   (a) The weight and the size of the array.

   (b) The reduction in convection coefficient with more closely spaced fins and the increase in total surface area.

   (c) The increase in convection coefficient and the increase in weight with more closely spaced fins.

   Answer:

8. Typical engineered phase-change cooling systems operate in:

   (a) the nucleate boiling regime, ensuring high cooling capacity, low excess temperatures, and a margin of safety.

   (b) at the critical point, ensuring maximum possible performance with small excess temperature.

   (c) In the film boiling regime, ensuring the combination of high excess temperature and high heat removal rates.

   Answer:

9. A large cavity with a small opening is approximately equivalent to a black surface because

   (a) it looks dark.

   (b) a photon entering the cavity is very unlikely to come back out.

   (c) no radiation ever emerges from inside the cavity to the outside.

   Answer:

10. The view factor F_{ij} between two objects i and j is:

   (a) the fraction of radiant energy emitted by i which impinges on j.
   (b) the fraction of radiant energy emitted by j which impinges on i.
   (c) the solid angle subtended by j as seen from i.

   Answer:

Part 2: Problems (25 points per question)
Attempt all problems in this section, clearly stating any assumptions and simplifications used in your solution

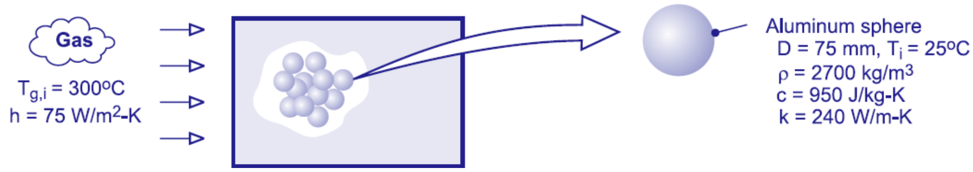

Figure 1: Schematic and parameters for a packed bed thermal energy storage system.

Problem 1

A packed-bed thermal energy storage system uses an array of aluminum spheres (initially at T_i) to collect the heat of incoming gas at $T_{g,i}$ (Fig. 1). Find the time required for a sphere to acquire 90% of its maximum possible thermal energy, estimate the corresponding temperature at the center of the sphere. Now replace aluminum spheres with copper spheres of the same diameter, assuming density 8900 kg/m^3 and heat capacity 400 J/(kg K) for copper. How will the energy stored by the array of copper spheres compare with that stored by the aluminum spheres?

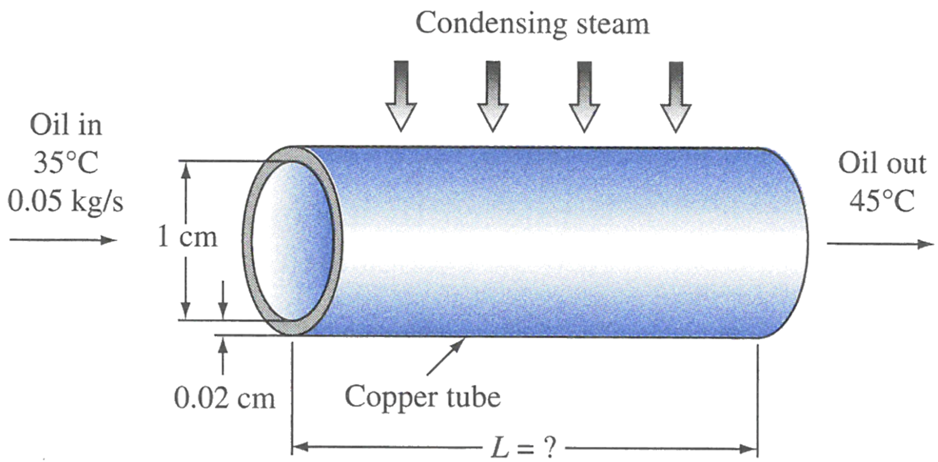

Figure 2: Schematic of oil-warming tube arrangement.

Problem 2

Used engine oil can be recycled by a patented processing system. This system includes a process during which the oil flows through a 1-cm internal diameter copper tube with a wall thickness of 0.02 cm, at a rate of 0.05 kg/s. the oil enters at 35°C and is to be heated to 45°C using atmospheric pressure steam condensing on the outside of the tube, as shown in figure 2. Calculate the length of tube required.

Problem 3

Water at atmospheric pressure is boiling on a mechanically polished stainless steel surface that is heated electrically from below. Determine the heat flux from the surface to the water when the surface temperature is 106°Cm and compare it with the critical heat flux for nucleate boiling.

Potentially useful information

Water at saturation pressure

Temperature, T			Density, ρ (kg/m^3)	Coefficient of Thermal Expansion, $\beta \times 10^4$ (1/K)	Specific Heat, c_p (J/kg K)	Thermal Conductivity, k (W/m K)	Thermal Diffusivity, $\alpha \times 10^6$ (m^2/s)	Absolute Viscosity, $\mu \times 10^6$ (N s/m^6)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2} \times 10^{-9}$ (1/K m^3)
°F	K	°C	$\times 6.243 \times 10^{-2}$ = (lb$_m$/ft^3)	$\times 0.5556$ = (1/R)	$\times 2.388 \times 10^{-4}$ = (Btu/lb$_m$ °F)	$\times 0.5777$ = (Btu/h ft °F)	$\times 3.874 \times 10^4$ = (ft^2/h)	$\times 0.6720$ = (lb$_m$/ft s)	$\times 3.874 \times 10^4$ = (ft^2/h)		$\times 1.573 \times 10^{-2}$ = (1/R ft^3)
32	273	0	999.9	−0.7	4226	0.558	0.131	1794	1.789	13.7	—
41	278	5	1000	—	4206	0.568	0.135	1535	1.535	11.4	—
50	283	10	999.7	0.95	4195	0.577	0.137	1296	1.300	9.5	0.551
59	288	15	999.1	—	4187	0.585	0.141	1136	1.146	8.1	—
68	293	20	998.2	2.1	4182	0.597	0.143	993	1.006	7.0	2.035
77	298	25	997.1	—	4178	0.606	0.146	880.6	0.884	6.1	—
86	303	30	995.7	3.0	4176	0.615	0.149	792.4	0.805	5.4	4.540
95	308	35	994.1	—	4175	0.624	0.150	719.8	0.725	4.8	—
104	313	40	992.2	3.9	4175	0.633	0.151	658.0	0.658	4.3	8.833
113	318	45	990.2	—	4176	0.640	0.155	605.1	0.611	3.9	—
122	323	50	988.1	4.6	4178	0.647	0.157	555.1	0.556	3.55	14.59
167	348	75	974.9	—	4190	0.671	0.164	376.6	0.366	2.23	—
212	373	100	958.4	7.5	4211	0.682	0.169	277.5	0.294	1.75	85.09
248	393	120	943.5	8.5	4232	0.685	0.171	235.4	0.244	1.43	140.0
284	413	140	926.3	9.7	4257	0.684	0.172	201.0	0.212	1.23	211.7
320	433	160	907.6	10.8	4285	0.680	0.173	171.6	0.191	1.10	290.3
356	453	180	886.6	12.1	4396	0.673	0.172	152.0	0.173	1.01	396.5
392	473	200	862.8	13.5	4501	0.665	0.170	139.3	0.160	0.95	517.2
428	493	220	837.0	15.2	4605	0.652	0.167	124.5	0.149	0.90	671.4
464	513	240	809.0	17.2	4731	0.634	0.162	113.8	0.141	0.86	848.5
500	533	260	779.0	20.0	4982	0.613	0.156	104.9	0.135	0.86	1076
536	553	280	750.0	23.8	5234	0.588	0.147	98.07	0.131	0.89	1360
572	573	300	712.5	29.5	5694	0.564	0.132	92.18	0.128	0.98	1766

(*Continued*)

Properties of water.

Saturation Temperature T			Saturation Pressure $p \times 10^{-5}$ (N/m²)	Specific Volume of Vapor v_g(m³/kg)	Enthalpy h_f (kJ/kg)	Enthalpy h_g (kJ/kg)	Enthalpy h_{fg} (kJ/kg)
°F	K	°C	× 1.450 × 10^{-4} = (psi)	× 16.02 = (ft³/lb$_m$)	× 0.430 = (Btu/lb$_m$)	× 0.430 = (Btu/lb$_m$)	× 0.430 = (Btu/lb$_m$)
32	273	0	0.0061	206.3	−0.04	2501	2501
50	283	10	0.0122	106.4	41.99	2519	2477
68	293	20	0.0233	57.833	83.86	2537	2453
86	303	30	0.0424	32.929	125.66	2555	2430
104	313	40	0.0737	19.548	167.45	2574	2406
122	323	50	0.1233	12.048	209.26	2591	2382
140	333	60	0.1991	7.680	251.09	2609	2358
158	343	70	0.3116	5.047	292.97	2626	2333
176	353	80	0.4735	3.410	334.92	2643	2308
194	363	90	0.7010	2.362	376.94	2660	2283
212	373	100	1.0132	1.673	419.06	2676	2257
248	393	120	1.9854	0.892	503.7	2706	2202
284	413	140	3.6136	0.508	589.1	2734	2144
320	433	160	6.1804	0.306	675.5	2757	2082
356	453	180	10.027	0.193	763.1	2777	2014
392	473	200	15.551	0.127	852.4	2791	1939
428	493	220	23.201	0.0860	943.7	2799	1856
464	513	240	33.480	0.0596	1037.6	2801	1764
500	533	260	46.940	0.0421	1135.0	2795	1660
536	553	280	64.191	0.0301	1237.0	2778	1541
572	573	300	85.917	0.0216	1345.4	2748	1403

Source: K. Raznjevič, *Handbook of Thermodynamic Tables and Charts,* McGraw-Hill, New York, 1976.

Properties of water ctd.

used engine oil

Temperature, T °F	K	°C	Density, ρ (kg/m^3) × 6.243 × 10^{-2} = (lb_m/ft^3)	Coefficient of Thermal Expansion, $\beta \times 10^3$ (1/K) × 0.5556 = (1/R)	Specific Heat, c_p (J/kg K) × 2.388 × 10^{-4} = (Btu/lb_m °F)	Thermal Conductivity, k (W/m K) × 0.5777 = (Btu/h ft °F)	Thermal Diffusivity, $\alpha \times 10^{10}$ (m^2/s) × 3.874 × 10^4 = (ft^2/h)	Absolute Viscosity, $\mu \times 10^3$ (N s/m^2) ×0.6720 = (lb_m/ft s)	Kinematic Viscosity, $\nu \times 10^6$ (m^2/s) × 3.874 × 10^4 = (ft^2/h)	Prandtl Number, Pr	$\frac{g\beta}{\nu^2}$ (1/K m^3) × 1.573 × 10^{-2} = (1/R ft^3)
32	273	0	899.1		1796	0.147	911	3848	4280	471	
68	293	20	888.2	0.648	1880	0.145	872	799	900	104	7.85×10^3
104	313	40	876.1	0.691	1964	0.144	834	210	240	28.7	1.18×10^5
140	333	60	864.0	0.697	2047	0.140	800	72.5	83.9	10.5	9.72×10^5
176	353	80	852.0	0.704	2131	0.138	769	32.0	37.5	4.90	4.91×10^6
212	373	100	840.0	0.684	2219	0.137	738	17.1	20.3	2.76	1.63×10^7
248	393	120	829.0	0.697	2307	0.135	710	10.3	12.4	1.75	4.44×10^7
284	413	140	816.9	0.706	2395	0.133	686	6.54	8.0	1.16	1.08×10^8
320	433	160	805.9		2483	0.132	663	4.51	5.6	0.84	—

Source: E. R. G. Eckert and R. M. Drake, *Analysis of Heat and Mass Transfer*, McGraw-Hill, New York, 1972.

Values of the coefficient C_{sf} for various liquid-surface combinations

Fluid-heating Surface Combination	C_{sf}
Water on scored copper [18][a]	0.0068
Water on emery-polished copper [18]	0.0128
Water-copper [25]	0.0130
Water on emery-polished, paraffin-treated copper [18]	0.0147
Water-brass [27]	0.0060
Water on Teflon coated stainless steel [18]	0.0058
Water on ground and polished stainless steel [18]	0.0080
Water on chemically etched stainless steel [18]	0.0133
Water on mechanically polished stainless steel [18]	0.0132
Water-platinum [19]	0.0130
n-Pentane on lapped copper [18]	0.0049
n-Pentane on emery-rubbed copper [18]	0.0074
n-Pentane on emery-polished copper [18]	0.0154
n-Pentane on emery-polished nickel [18]	0.0127
n-Pentane-chromium [26]	0.0150
Isopropyl alcohol-copper [25]	0.00225
n-Butyl alcohol-copper [25]	0.00305
Ethyl alcohol-chromium [26]	0.0027
Carbon tetrachloride on emery-polished copper [18]	0.0070
Carbon tetrachloride-copper [25]	0.0130
Benzene-chromium [26]	0.0100
50% K_2CO_3-copper [25]	0.00275
35% K_2CO_3-copper [25]	0.0054

[a]Numbers in brackets indicate references

Vapor-liquid surface tension for water

Surface Tension $\sigma(\times 10^3$ N/m)	**Saturation Temperature °C**
75.5	0
72.9	20
69.5	40
66.1	60
62.7	80
58.9	100
48.7	150
37.8	200
26.1	250
14.3	300
3.6	350

Source: N. B. Vargaftik. *Tables on the Thermophysical Properties of Liquids and Gases*, 2nd ed., Hemisphere. Washington. DC, 1975, p. 53.