University of New Mexico
Mechanical Engineering
Spring 2008 PhD qualifying examination
Heat Transfer

Closed book. Formula sheet and calculator allowed, but not cell phones, computers or any other wireless device.
Time allowed: 150 minutes.

Part 1: General knowledge questions

1. Which statement best describes the process of conduction:

   (a) heat transfered by photons moving through space
   (b) heat transfered by phonons in a material
   (c) heat advected by a flowing fluid

   Answer:

2. A high Biot number in the context of a solid immersed in a fluid means:

   (a) poor convection, good conduction
   (b) poor conduction, good convection
   (c) uniform temperature in the solid during transients

   Answer:

3. The underlying assumption when the lumped capacitance method is used to solve transient heat conduction problems is:

   (a) constant temperature in time
   (b) uniform temperature through the material in question
   (c) high heat capacity in the material in question

   Answer:

4. A laminated composite material, composed of different layers glued together, the steady-state heat transfer across the thickness of the material can be modeled by:

   (a) a circuit of resistors in series
   (b) a series of resistors in parallel
   (c) resistors in a Wheatstone bridge configuration

   Answer:

5. The Fourier number can be thought of as:

   (a) a dimensionless measure of size
   (b) a dimensionless measure of the heat capacitance of a material
   (c) a dimensionless measure of time

   Answer:

6. At a fluid/solid interface in a flow with a high Prandtl number, the following holds:
   (a) the velocity boundary layer grows faster than the thermal boundary layer
   (b) the thermal boundary layer grows faster than the velocity boundary layer
   (c) the boundary layers grow at the same rate

   Answer:

7. For convection associated with flow inside a pipe, turbulence implies:
   (a) higher heat transfer rate
   (b) higher pressure loss
   (c) higher heat transfer rate and lower pressure loss

   Answer:

8. Doubling the length of a fin designed to remove heat from an electronic component would:
   (a) double the rate of heat removal
   (b) not affect the rate of heat removal
   (c) change the rate of heat removal by a factor which depends on many things, too many to list in a multiple choice question

   Answer:

9. Which of the following characteristics applies to a grey surface?
   (a) emits thermal radiation equally in all directions
   (b) emits radiation only in grey part of the spectrum
   (c) emits radiation equally for the entire visible spectrum, but not the infrared part

   Answer:

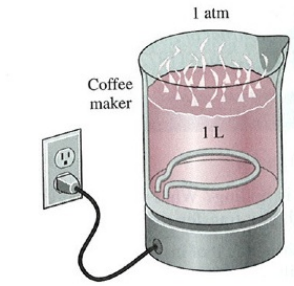
10. What part of the electromagnetic spectrum is occupied by thermal radiation?
    (a) ultraviolet, visible and infrared
    (b) infrared only
    (c) infrared to microwave

    Answer:

Part 2: Problems

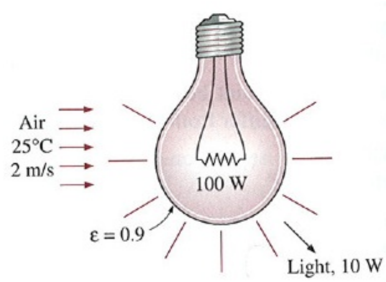
Attempt all problems in this section, clearly stating any assumptions and simplifications used in your solution.

Problem 1



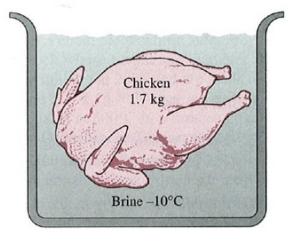
Water is boiled at sea level in a coffee-maker equipped with a 20-cm long, 0.4-cm diameter immersed electric heating element made of mechanically polished stainless steel. The coffee maker initially contains 1 L of water at 18°C. Once boiling starts, it is observed that half of the water in the coffee maker evaporates in 25 minutes. Determine the power rating of the electric heating element and its surface temperature during boiling. Also determine the time required to bring the temperature of the original 1 L of water to boiling.

Problem 2



Consider a 10-cm diameter incandescent light bulb rated at 100W. Air at 25°C blows across the bulb at 2 m/s. The bulb is in a room where the walls are also at 25°C. It can be assumed that 10% of the thermal radiation emitted by the filament passes through the glass, while the remainder is absorbed by it. If the emissivity of the glass is 0.9, determine the equilibrium temperature of the bulb.

Problem 3



Mass-produced, Soylent Green imitation-chickens have a mass of 1.7 kg, a thermal conductivity k of 0.45 W/m·K and a thermal diffusivity α of 0.13×10^{-6} m^2/s, and are at a temperature of 15°C after the final injection-molding process. To prepare for shipping and distribution, the simulated chickens are chilled in agitated brine at -10°C. The average convection coefficient between the pseudo-birds and the brine is determined experimentally to be 440 W/m^2·K. If the density of the meat is 950 kg/m^3, and assuming that the shape of the chicken-like product is approximately spherical, determine the center and surface temperatures after 150 minutes. Will any part of the delicacy be spoiled by freezing?

A properties of water

Properties of saturated water

Temp., T °F	Saturation Pressure, P_{sat}, psia	Density, ρ lbm/ft³ Liquid	Density, ρ lbm/ft³ Vapor	Enthalpy of Vaporization, h_{fg} Btu/lbm	Specific Heat, C_p Btu/lbm · °F Liquid	Specific Heat, C_p Btu/lbm · °F Vapor	Thermal Conductivity, k Btu/h · ft · °F Liquid	Thermal Conductivity, k Btu/h · ft · °F Vapor	Dynamic Viscosity, μ lbm/ft · h Liquid	Dynamic Viscosity, μ lbm/ft · h Vapor	Prandtl Number, Pr Liquid	Prandtl Number, Pr Vapor	Volume Expansion Coefficient, β 1/R Liquid
32.02	0.0887	62.41	0.00030	1075	1.010	0.446	0.324	0.0099	4.336	0.0223	13.5	1.00	-0.038×10^{-3}
40	0.1217	62.42	0.00034	1071	1.004	0.447	0.329	0.0100	3.740	0.0226	11.4	1.01	0.003×10^{-3}
50	0.1780	62.41	0.00059	1065	1.000	0.448	0.335	0.0102	3.161	0.0229	9.44	1.01	0.047×10^{-3}
60	0.2563	62.36	0.00083	1060	0.999	0.449	0.341	0.0104	2.713	0.0232	7.95	1.00	0.080×10^{-3}
70	0.3632	62.30	0.00115	1054	0.999	0.450	0.347	0.0106	2.360	0.0236	6.79	1.00	0.115×10^{-3}
80	0.5073	62.22	0.00158	1048	0.999	0.451	0.352	0.0108	2.075	0.0240	5.89	1.00	0.145×10^{-3}
90	0.6988	62.12	0.00214	1043	0.999	0.453	0.358	0.0110	1.842	0.0244	5.14	1.00	0.174×10^{-3}
100	0.9503	62.00	0.00286	1037	0.999	0.454	0.363	0.0112	1.648	0.0248	4.54	1.01	0.200×10^{-3}
110	1.2763	61.86	0.00377	1031	0.999	0.456	0.367	0.0115	1.486	0.0252	4.05	1.00	0.224×10^{-3}
120	1.6945	61.71	0.00493	1026	0.999	0.458	0.371	0.0117	1.348	0.0256	3.63	1.00	0.246×10^{-3}
130	2.225	61.55	0.00636	1020	0.999	0.460	0.375	0.0120	1.230	0.0260	3.28	1.00	0.267×10^{-3}
140	2.892	61.38	0.00814	1014	0.999	0.463	0.378	0.0122	1.129	0.0264	2.98	1.00	0.287×10^{-3}
150	3.722	61.19	0.0103	1008	1.000	0.465	0.381	0.0125	1.040	0.0269	2.73	1.00	0.306×10^{-3}
160	4.745	60.99	0.0129	1002	1.000	0.468	0.384	0.0128	0.963	0.0273	2.51	1.00	0.325×10^{-3}
170	5.996	60.79	0.0161	996	1.001	0.472	0.386	0.0131	0.894	0.0278	2.90	1.00	0.346×10^{-3}
180	7.515	60.57	0.0199	990	1.002	0.475	0.388	0.0134	0.834	0.0282	2.15	1.00	0.367×10^{-3}
190	9.343	60.35	0.0244	984	1.004	0.479	0.390	0.0137	0.781	0.0287	2.01	1.00	0.382×10^{-3}
200	11.53	60.12	0.0297	978	1.005	0.483	0.391	0.0141	0.733	0.0291	1.88	1.00	0.395×10^{-3}
210	14.125	59.87	0.0359	972	1.007	0.487	0.392	0.0144	0.690	0.0296	1.77	1.00	0.412×10^{-3}
212	14.698	59.82	0.0373	970	1.007	0.488	0.392	0.0145	0.682	0.0297	1.75	1.00	0.417×10^{-3}
220	17.19	59.62	0.0432	965	1.009	0.492	0.393	0.0148	0.651	0.0300	1.67	1.00	0.429×10^{-3}
230	20.78	59.36	0.0516	959	1.011	0.497	0.394	0.0152	0.616	0.0305	1.58	1.00	0.443×10^{-3}
240	24.97	59.09	0.0612	952	1.013	0.503	0.394	0.0156	0.585	0.0310	1.50	1.00	0.462×10^{-3}
250	29.82	58.82	0.0723	946	1.015	0.509	0.395	0.0160	0.556	0.0310	1.43	1.00	0.480×10^{-3}
260	35.42	58.53	0.0850	939	1.018	0.516	0.395	0.0164	0.530	0.0319	1.37	1.00	0.497×10^{-3}
270	41.85	58.24	0.0993	932	1.020	0.523	0.395	0.0168	0.506	0.0324	1.31	1.01	0.514×10^{-3}
280	49.18	57.94	0.1156	925	1.023	0.530	0.395	0.0172	0.484	0.0328	1.25	1.01	0.532×10^{-3}
290	57.53	57.63	0.3390	918	1.026	0.538	0.395	0.0177	0.464	0.0333	1.21	1.01	0.549×10^{-3}
300	66.98	57.31	0.1545	910	1.029	0.547	0.394	0.0182	0.445	0.0338	1.16	1.02	0.566×10^{-3}
320	89.60	56.65	0.2033	895	1.036	0.567	0.393	0.0191	0.412	0.0347	1.09	1.03	0.636×10^{-3}
340	117.93	55.95	0.2637	880	1.044	0.590	0.391	0.0202	0.383	0.0356	1.02	1.04	0.656×10^{-3}
360	152.92	55.22	0.3377	863	1.054	0.617	0.389	0.0213	0.359	0.0365	0.973	1.06	0.681×10^{-3}
380	195.60	54.46	0.4275	845	1.065	0.647	0.385	0.0224	0.337	0.0375	0.932	1.08	0.720×10^{-3}
400	241.1	53.65	0.5359	827	1.078	0.683	0.382	0.0237	0.318	0.0384	0.893	1.11	0.771×10^{-3}
450	422.1	51.46	0.9082	775	1.121	0.799	0.370	0.0271	0.278	0.0407	0.842	1.20	0.912×10^{-3}
500	680.0	48.95	1.479	715	1.188	0.972	0.352	0.0312	0.246	0.0432	0.830	1.35	1.111×10^{-3}
550	1046.7	45.96	4.268	641	1.298	1.247	0.329	0.0368	0.219	0.0461	0.864	1.56	1.445×10^{-3}
600	1541	42.32	3.736	550	1.509	1.759	0.299	0.0461	0.194	0.0497	0.979	1.90	1.885×10^{-3}
650	2210	37.31	6.152	422	2.086	3.103	0.267	0.0677	0.167	0.0555	1.30	2.54	—
700	3090	27.28	13.44	168	13.80	25.90	0.254	0.1964	0.123	0.0736	6.68	9.71	—
705.44	3204	19.79	19.79	0	∞	∞	∞	∞	0.104	0.1043	—	—	—

Note 1: Kinematic viscosity ν and thermal diffusivity α can be calculated from their definitions, $\nu = \mu/\rho$ and $\alpha = k/\rho C_p = \nu/\mathrm{Pr}$. The temperatures 32.02°F, 212°F, and 705.44°F are the triple-, boiling-, and critical-point temperatures of water, respectively. All properties listed above (except the vapor density) can be used at any pressure with negligible error except at temperatures near the critical-point value.

Note 2: The unit Btu/lbm · °F for specific heat is equivalent to Btu/lbm · R, and the unit Btu/h · ft · °F for thermal conductivity is equivalent to Btu/h · ft · R.

Source: Viscosity and thermal conductivity data are from J. V. Sengers and J. T. R. Watson, *Journal of Physical and Chemical Reference Data* 15 (1986), pp. 1291–322. Other data are obtained from various sources or calculated.

B boiling data

$$\dot{q}_{\text{nucleate}} = \mu_l\, h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{C_p(T_s - T_{\text{sat}})}{C_{sf}\, h_{fg}\, \mathrm{Pr}_l^n}\right]^3$$

$$\dot{q}_{\max} = C_{cr}\, h_{fg}[\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4}$$

$$\dot{q}_{\min} = 0.09\rho_v\, h_{fg}\left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4}$$

Values of the coefficient C_{sf} and n for various fluid–surface combinations

Fluid-Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper (polished)	0.0154	1.7
n-Pentane–chromium	0.0150	1.7
Benzene–chromium	0.1010	1.7
Ethyl alcohol–chromium	0.0027	1.7
Carbon tetrachloride–copper	0.0130	1.7
Isopropanol–copper	0.0025	1.7

Surface tension of liquid–vapor interface for water

T, °C	σ, N/m*
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0,0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s².

Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

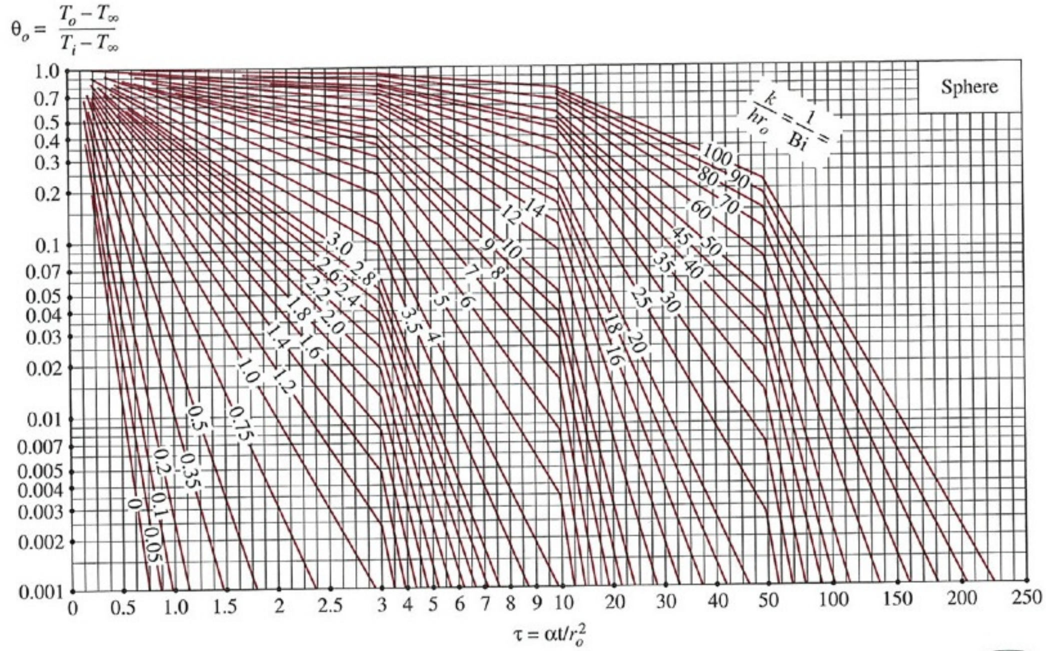
Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{\text{heater}}]$

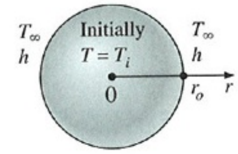
C series solution for transients

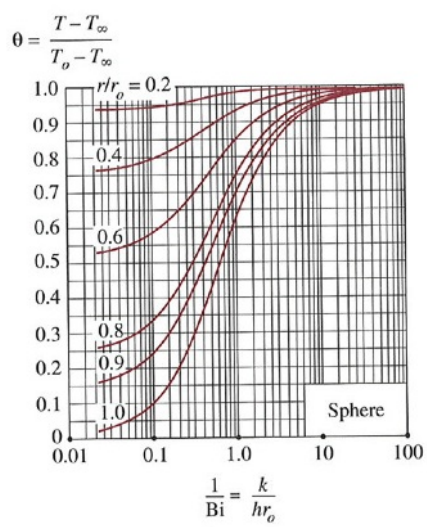
Coefficients used in the one-term approximate solution of transient one-dimensional heat conduction in plane walls, cylinders, and spheres (Bi = hL/k for a plane wall of thickness $2L$, and Bi = hr_o/k for a cylinder or sphere of radius r_o)

	Plane Wall		Cylinder		Sphere	
Bi	λ_1	A_1	λ_1	A_1	λ_1	A_1
0.01	0.0998	1.0017	0.1412	1.0025	0.1730	1.0030
0.02	0.1410	1.0033	0.1995	1.0050	0.2445	1.0060
0.04	0.1987	1.0066	0.2814	1.0099	0.3450	1.0120
0.06	0.2425	1.0098	0.3438	1.0148	0.4217	1.0179
0.08	0.2791	1.0130	0.3960	1.0197	0.4860	1.0239
0.1	0.3111	1.0161	0.4417	1.0246	0.5423	1.0298
0.2	0.4328	1.0311	0.6170	1.0483	0.7593	1.0592
0.3	0.5218	1.0450	0.7465	1.0712	0.9208	1.0880
0.4	0.5932	1.0580	0.8516	1.0931	1.0528	1.1164
0.5	0.6533	1.0701	0.9408	1.1143	1.1656	1.1441
0.6	0.7051	1.0814	1.0184	1.1345	1.2644	1.1713
0.7	0.7506	1.0918	1.0873	1.1539	1.3525	1.1978
0.8	0.7910	1.1016	1.1490	1.1724	1.4320	1.2236
0.9	0.8274	1.1107	1.2048	1.1902	1.5044	1.2488
1.0	0.8603	1.1191	1.2558	1.2071	1.5708	1.2732
2.0	1.0769	1.1785	1.5995	1.3384	2.0288	1.4793
3.0	1.1925	1.2102	1.7887	1.4191	2.2889	1.6227
4.0	1.2646	1.2287	1.9081	1.4698	2.4556	1.7202
5.0	1.3138	1.2403	1.9898	1.5029	2.5704	1.7870
6.0	1.3496	1.2479	2.0490	1.5253	2.6537	1.8338
7.0	1.3766	1.2532	2.0937	1.5411	2.7165	1.8673
8.0	1.3978	1.2570	2.1286	1.5526	2.7654	1.8920
9.0	1.4149	1.2598	2.1566	1.5611	2.8044	1.9106
10.0	1.4289	1.2620	2.1795	1.5677	2.8363	1.9249
20.0	1.4961	1.2699	2.2880	1.5919	2.9857	1.9781
30.0	1.5202	1.2717	2.3261	1.5973	3.0372	1.9898
40.0	1.5325	1.2723	2.3455	1.5993	3.0632	1.9942
50.0	1.5400	1.2727	2.3572	1.6002	3.0788	1.9962
100.0	1.5552	1.2731	2.3809	1.6015	3.1102	1.9990
∞	1.5708	1.2732	2.4048	1.6021	3.1416	2.0000

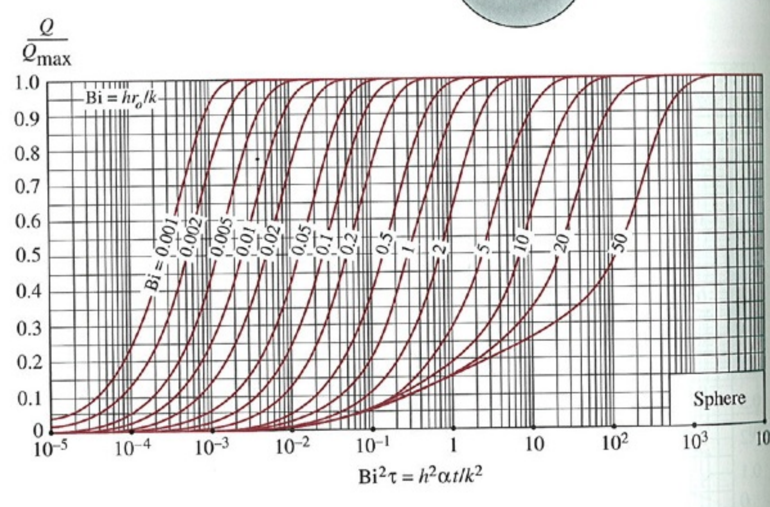


(*a*) Midpoint temperature (from M. P. Heisler)





(*b*) Temperature distribution (from M. P. Heisler)



(*c*) Heat transfer (from H. Gröber et al.)