University of New Mexico
Mechanical Engineering
Fall 2012 PhD qualifying examination
Heat Transfer

Closed book. Formula sheet and calculator are allowed, but not cell phones, computers or any other wireless device.

Time allowed: 150 minutes.

Part 1: General knowledge questions (25 points)

1. Nusselt number...

   (a) is a measure of heat transfer enhancement via convection (as compared with conduction).
   (b) is the ratio of thermal to mechanical dissipation.
   (c) equals the ratio of convective heat transfer coefficient h to conducivity k.

   Answer:

2. Objects that radiate relatively well

   (a) always absorb radiation relatively well.
   (b) reflect radiation relatively well.
   (c) have a high emissivity ε.

   Answer:

3. Why do ceramic tiles in a kitchen or bathroom feel cooler than a floor mat?

   (a) ceramic has a lower thermal conductivity value.
   (b) ceramic has a higher contact area with your feet.
   (c) ceramic has a higher thermal conductivity value

   Answer:

4. The cooking instructions for turkeys always always tell us to measure temperature deep inside the turkey. From this, we can infer that, for the typical baking conditions:

   (a) the Biot number is low
   (b) the Biot number is high
   (c) the thermometer will fall off unless we stick it in deep enough

   Answer:

5. Why is it acceptable to use only one term in the infinite series solution for transient problems with large Biot numbers, if the Fourier number is large?

   (a) the high-frequency terms in the solution decay quickly with time
   (b) the low-frequency terms in the solution decay quickly with time
   (c) the Krylov space of the higher terms is range-deficient and therefore does not contribute to the solution

   Answer:

6. In a process where heat is removed by nucleate boiling, it is generally important to make sure that the critical heat flux is not exceeded. This is because:

   (a) if critical flux is exceeded, the boiling process could become unstable and create excessive vibration on the system

   (b) Exceeding the critical flux may result in a reduction in the temperature, leading to reduced heat transfer

   (c) Exceeding the critical heat flux results in an almost instantaneous very large increase in temperature

   Answer:

7. Certain frypans have a thick metal handle rather than a wooden one. This is because:

   (a) A thick metal handle dissipates heat better and is therefore cooler

   (b) The frypan can be placed directly in the oven

   (c) The frypan is better balanced

   Answer:

8. Birds "fluff" their feathers while perching in cold weather because:

   (a) They tend to preen more in the winter because there is less to do

   (b) Feathers standing on end provide a thicker layer of still air with better insulating properties

   (c) they are trying to deter predators by looking bigger

   Answer:

9. There exists an optimum fin spacing for arrays of naturally convecting fins. This is because:

   (a) placing fins closer together enhances natural convection

   (b) placing fins further apart enhances natural convection

   (c) placing fins closer together degrades natural convection, but increases the available area for heat transfer

   Answer:

10. Doubling the length of a pin fin results in:

    (a) a doubling of the heat transfer from the fin

    (b) no change

    (c) an increase in heat transfer by a factor smaller than 2

    Answer:

Part 2: Problems (25 points per question)

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

Problem 1

Given: A mild carbon steel plate (AISI 1042) of thickness 1 cm at a temperature 600°C is rapidly immersed in an oil bath at 30°C. The average convective heat transfer coefficient between the plate and the oil is known to be about $400\mathrm{W/m^2K}$.
Find: The time it will take for the plate to cool to 90°C.

Note: For steel, assume $\rho = 7800$ kg/m^3, $c = 450$ J/(kg K). Also use the attached tables if necessary. Justify your assumptions regarding the method of solution.

Problem 2

Given: A 20-m steam pipe is insulated on the outside with a layer of 85% magnesia insulation. The pipe wall thickness is 7 mm, the outer diameter of the pipe is 150 mm, the insulation layer thickness is 50 mm. The pipe is made of AISI 1010 mild steel. Inside the pipe, superheated steam flows at 230°C, with the convective heat transfer coefficient between the steam flow and the inner wall of the pipe 35 W/m^2K. On the outside of the pipe, the ambient temperature is 20°C. The convection coefficient between the insulated pipe and the surroundings is 8 W/m^2K.
Find: Heat dissipated from the pipe to the surroundings.

Note: Use the attached tables for reference.

Problem 3

A black sphere of diameter 2.5 cm is at thermal equilibrium when the quiescent air surrounding it is at $20°C$, and the walls of a large surrounding enclosure are at 1000K. What is the temperature of the sphere?

Note: The Stefan-Boltzmann constant σ is approximately $5.67 \times 10^{-8} \mathrm{W/m^2K^4}$.

Table A.1*b* Solid metals: Temperature dependence of thermal conductivity k [W/m K] (see Table A.1*a* for metal compositions)

Metal	Temperature, K								
	200	300	400	500	600	800	1000	1200	1500
Aluminum									
Pure	237	237	240	236	231	218			
Duralumin	138	174	187	188					
Alloy 195, cast		168	174	180	185				
Copper									
Pure	413	401	393	386	379	366	352	339	
Commercial bronze	42	52	52	55					
Brass	74	111	134	143	146	150			
German silver		116	135	145	147				
Gold	323	317	311	304	298	284	270	255	
Iron									
Armco	81	73	66	59	53	42	32	29	31
Cast		51	44	39	36	27	23		
Carbon steels									
AISI 1010		64	59	54	49	39	31		
AISI 1042		52	50	48	45	37	29	26	30
AISI 4130		43	42	41	40	37	31	27	31
Stainless steels									
AISI 302		15	17	19	20	23	25		
AISI 304	13	15	17	18	20	23	25		
AISI 316		13	15	17	18	21	24		
AISI 410	25	25	26	27	27	29			
Lead	37	35	34	33	31				
Magnesium									
Pure	199	156	153	151	149	146			
Alloy A8			84						
Nickel									
Pure	105	91	80	72	66	68	72	76	83
Inconel-X-750	10.3	11.7	13.5	15.1	17.0	20.5	24.0	27.6	30.0
Nichrome		13	14	16	17	21			
Platinum	73	72	72	72	73	76	79	83	90
Silver	420	429	425	419	412	396	379	361	
Tantalum	58	58	58	59	59	59	60	61	62
Tin	73	67	62	60					
Titanium									
Pure	25	22	20	20	19	19	21	22	25
Ti-6Al-4V		5.8							
Tungsten	185	174	159	146	137	125	118	112	106
Zirconium									
Pure	25	23	22	21	21	21	23	26	29
Zircaloy-4	13.3	14.2	15.2	16.2	17.2	19.2	21.2	23.2	

Table A.3 *(Concluded)*

	T K	ρ kg/m^3	c J/kg K	k W/m K	α m^2/s$\times 10^6$
Loose fill					
Cellulose, wood or paper pulp	290			0.038	
	300	45		0.039	
	310			0.042	
Vermiculite, expanded	240			0.058	
	260			0.061	
	280			0.064	
	300	122		0.069	
	320			0.074	
	240			0.052	
	260			0.056	
	280			0.059	
	300	80		0.063	
	320			0.068	
Magnesia	300	270		0.062	
(85 %)	350			0.068	
	400			0.073	
	450			0.078	
	500			0.082	
Paper	300	930	2500	0.13	0.056
Polystyrene, rigid	240			0.023	
	260			0.024	
	280			0.026	
	300	30–60	1210	0.028	0.4–0.8
	320			0.030	
Polyurethane, rigid foam	300	70		0.026	
Rubber					
Hard	270	1200	2010	0.15	0.062
Neoprene	300	1250	1930	0.19	0.079
Rigid foamed	260			0.028	
	280			0.030	
	300	70		0.032	
	320			0.034	
Snow	273	110		0.049	
		500		0.190	
Soil					
Dry	300	1500	1900	1.0	0.35
Wet	300	1900	2200	2.0	0.5
Woods					
Oak, parallel to grain	300	820	2400	0.35	0.18
perpendicular to grain	300	820	2400	0.21	0.11
White Pine, parallel to grain	300	500	2800	0.24	0.17
perpendicular to grain	300	500	2800	0.10	0.071
Wool, sheep	300	145		0.05	

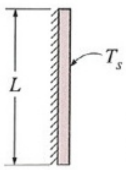
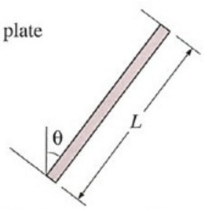
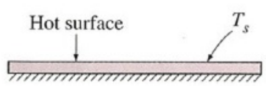
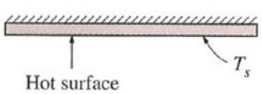
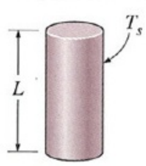
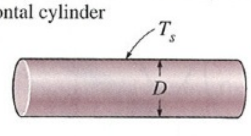
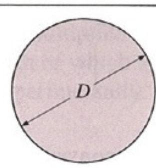
Properties of air at 1 atm pressure

Temp., T, °F	Density, ρ, lbm/ft^3	Specific Heat, C_p, Btu/lbm · °F	Thermal Conductivity, k, Btu/h · ft · °F	Thermal Diffusivity, α, ft^2/h	Dynamic Viscosity, μ, lbm/ft · h	Kinematic Viscosity, ν, ft^2/h	Prandtl Number, Pr
−300	0.24844	0.5072	0.00508	0.0403	0.01454	0.0585	1.4501
−200	0.15276	0.2247	0.00778	0.2266	0.02438	0.1596	0.7042
−100	0.11029	0.2360	0.01037	0.3985	0.03255	0.2951	0.7404
−50	0.09683	0.2389	0.01164	0.5029	0.03623	0.3741	0.7439
0	0.08630	0.2401	0.01288	0.6215	0.03970	0.4601	0.7403
10	0.08446	0.2402	0.01312	0.6468	0.04038	0.4781	0.7391
20	0.08270	0.2403	0.01336	0.6726	0.04104	0.4963	0.7378
30	0.08101	0.2403	0.01361	0.6990	0.04170	0.5148	0.7365
40	0.07939	0.2404	0.01385	0.7259	0.04236	0.5335	0.7350
50	0.07783	0.2404	0.01409	0.7532	0.04300	0.5525	0.7336
60	0.07633	0.2404	0.01433	0.7810	0.04365	0.5718	0.7321
70	0.07489	0.2404	0.01457	0.8093	0.04428	0.5913	0.7306
80	0.07350	0.2404	0.01481	0.8381	0.04491	0.6110	0.7290
90	0.07217	0.2404	0.01505	0.8673	0.04554	0.6310	0.7275
100	0.07088	0.2405	0.01529	0.8969	0.04615	0.6512	0.7260
110	0.06963	0.2405	0.01552	0.9270	0.04677	0.6716	0.7245
120	0.06843	0.2405	0.01576	0.9575	0.04738	0.6923	0.7230
130	0.06727	0.2405	0.01599	0.9884	0.04798	0.7132	0.7216
140	0.06615	0.2406	0.01623	1.0198	0.04858	0.7344	0.7202
150	0.06507	0.2406	0.01646	1.0515	0.04917	0.7558	0.7188
160	0.06402	0.2406	0.01669	1.0836	0.04976	0.7774	0.7174
170	0.06300	0.2407	0.01692	1.1160	0.05035	0.7992	0.7161
180	0.06201	0.2408	0.01715	1.1489	0.05093	0.8213	0.7148
190	0.06106	0.2408	0.01738	1.1821	0.05151	0.8435	0.7136
200	0.06013	0.2409	0.01761	1.2156	0.05208	0.8660	0.7124
250	0.05590	0.2415	0.01874	1.3884	0.05488	0.9818	0.7071
300	0.05222	0.2423	0.01985	1.5690	0.05758	1.1027	0.7028
350	0.04899	0.2433	0.02094	1.7566	0.06020	1.2288	0.6995
400	0.04614	0.2445	0.02200	1.9507	0.06274	1.3598	0.6971
450	0.04361	0.2458	0.02305	2.1508	0.06522	1.4955	0.6953
500	0.04134	0.2472	0.02408	2.3565	0.06762	1.6359	0.6942
600	0.03743	0.2503	0.02608	2.7834	0.07225	1.9300	0.6934
700	0.03421	0.2535	0.02800	3.2292	0.07666	2.2411	0.6940
800	0.03149	0.2568	0.02986	3.6925	0.08088	2.5684	0.6956
900	0.02917	0.2599	0.03164	4.1721	0.08494	2.9112	0.6978
1000	0.02718	0.2630	0.03336	4.6671	0.08883	3.2688	0.7004
1500	0.02024	0.2761	0.04106	7.3465	0.10644	5.2584	0.7158
2000	0.01613	0.2855	0.04752	10.3200	0.12163	7.5418	0.7308
2500	0.01340	0.2922	0.05309	13.5532	0.13501	10.0733	0.7432
3000	0.01147	0.2972	0.05811	17.0526	0.14696	12.8170	0.7516
3500	0.01002	0.3010	0.06293	20.8709	0.15771	15.7428	0.7543
4000	0.00889	0.3040	0.06789	25.1094	0.16745	18.8252	0.7497

Note: For ideal gases, the properties C_p, k, μ, and Pr are independent of pressure. The properties ρ, ν, and α at a pressure P (in atm) other than 1 atm are determined by multiplying the values of ρ at the given temperature by P and by dividing ν and α by P.

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Keenan, Chao, Keyes, Gas Tables, Wiley, 198; and *Thermophysical Properties of Matter,* Vol. 3: *Thermal Conductivity,* Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: *Viscosity,* Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenun, NY, 1970, ISBN 0-306067020-8.

Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu	
Vertical plate 	L	10^4–10^9 10^9–10^{13} Entire range	$\text{Nu} = 0.59\text{Ra}_L^{1/4}$ $\text{Nu} = 0.1\text{Ra}_L^{1/3}$ $\text{Nu} = \left\{0.825 + \frac{0.387\text{Ra}_L^{1/6}}{[1 + (0.492/\text{Pr})^{9/16}]^{8/27}}\right\}^2$ (complex but more accurate)	(9-19) (9-20) (9-21)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g \cos\theta$ for $\text{Ra} < 10^9$	
Horiontal plate (Surface area A and perimeter p) (*a*) Upper surface of a hot plate (or lower surface of a cold plate)  (*b*) Lower surface of a hot plate (or upper surface of a cold plate) 	A_s/p	10^4–10^7 10^7–10^{11} 10^5–10^{11}	$\text{Nu} = 0.54\text{Ra}_L^{1/4}$ $\text{Nu} = 0.15\text{Ra}_L^{1/3}$ $\text{Nu} = 0.27\text{Ra}_L^{1/4}$	(9-22) (9-23) (9-24)
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{\text{Gr}_L^{1/4}}$	
Horizontal cylinder 	D	$\text{Ra}_D \leq 10^{12}$	$\text{Nu} = \left\{0.6 + \frac{0.387\text{Ra}_D^{1/6}}{[1 + (0.559/\text{Pr})^{9/16}]^{8/27}}\right\}^2$	(9-25)
Sphere 	D	$\text{Ra}_D \leq 10^{11}$ ($\text{Pr} \geq 0.7$)	$\text{Nu} = 2 + \frac{0.589\text{Ra}_D^{1/4}}{[1 + (0.469/\text{Pr})^{9/16}]^{4/9}}$	(9-26)