University of New Mexico
Mechanical Engineering
Spring 2011 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. In convection, heat is transported by:
   (a) fluid advection only.
   (b) a combination of conduction and advection.
   (c) It depends on whether the medium is a liquid or a gas.

   Answer:

2. Which mode of heat transfer does not require an intervening medium?
   (a) Conduction.
   (b) Radiation.
   (c) Convection.

   Answer:

3. In radiant heat transfer, a perfect emitter must also be a perfect absorber. Why?
   (a) If it were not so, it would be possible to build a device that violates the second law of thermodynamics.
   (b) There is no known reason, but measurements always follow this rule.
   (c) There is no such thing as a perfect emitter or absorber.

   Answer:

4. In radiant heat transfer, a small aperture to a large cavity approximates:
   (a) A blackbody.
   (b) A gray body.
   (c) A selective emitter.

   Answer:

5. The purpose of goose down in a ski jacket is to:
   (a) cushion falls.
   (b) retain air and prevent its motion, thereby increasing the thermal resistance of the jacket.
   (c) retain air and prevent its motion, thereby decreasing the thermal resistance of the jacket.

   Answer:

6. At a large scale, wind is an example of:
   (a) Forced convection.
   (b) Natural (buoyancy-driven) convection.
   (c) The interaction of forced convection and natural convection.

   Answer:

7. Which of the following objects of equal volume would have the smallest Biot number, under the same ambient conditions?
   (a) A cube.
   (b) A sphere.
   (c) A thin sheet.

   Answer:

8. In a boiling water nuclear reactor, water in contact with the nuclear fuel rods removes heat by changing phase. Where on the boiling curve should the reactor operate?
   (a) In the nucleate boiling regime.
   (b) At critical heat flux, for maximum efficiency.
   (c) In the film boiling regime.

   Answer:

9. The Nusselt number and the Biot number are defined as dimensionless groups involving the same combination of parameters. Are they interchangeable?
   (a) Yes, generally the French prefer to call this group the Biot number, while the Germans and Austrians call it the Nusselt number. Americans are neutral on the issue, and use the groups interchangeably.
   (b) No, one defines the ratio of convective and conductive thermal resistance, the other is a measure of the dimensionless temperature gradient at a surface.
   (c) No, The Biot number relates strictly to conduction, while the Nusselt number is used strictly for convection.

   Answer:

10. The Fourier number is a measure of:
    (a) Dimensionless position.
    (b) Dimensionless temperature.
    (c) Dimensionless time.

    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

During a cold winter night, a glycol-water mixture is circulated through a solar system to prevent freezing. In a particular section of the system, crows removed the pipe insulation, so that a short section of pipe is exposed directly to the elements. To assess the risk of freezing, an engineer (i.e. you, the student taking this test) makes a set of worst-case assumptions, as follows:

1. The temperature of the air is -20°C, and there is a 20 m/s wind perpendicular to the tube;
2. The bulk temperature of the glycol/water mixture entering the tube is 13°C;
3. The flow rate through the tube is 0.180 liters/s;
4. The length of the exposed section of tube is 0.5 m.

The inner diameter of the copper tube is 20 mm, and the wall is 1 mm thick. The thermal conductivity of the glycol / water mixture is 0.42 W/m·K, the density is 1045 kg/m^3, the specific heat 3720 J/kg·K, and the dynamic vicosity is 12.5×10^{-3} Pa·s.

Your task, then, is to calculate:

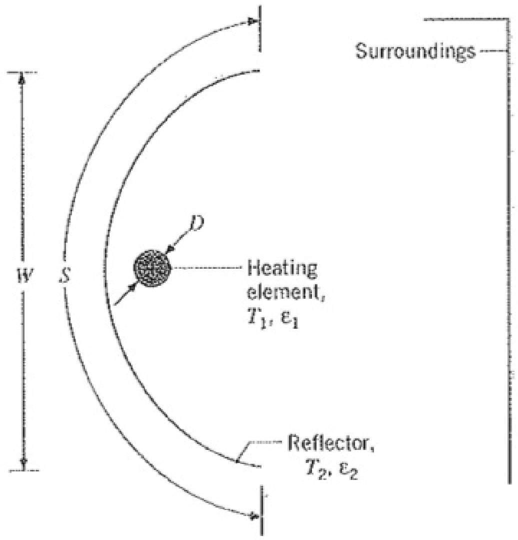
1. The convection coefficient for the flow inside the pipe;
2. The convection coefficient for the flow outside of the pipe;
3. The temperature of the pipe wall, assuming this is constant;
4. The rate of heat loss from the glycol/water mixture to the air;
5. The bulk temperature of the glycol water mixture as it leaves the exposed section of pipe.

State any simplifying assumptions.

Problem 2

In a material treatment process, a metallic sphere 10 mm in diameter that is initially at 400°C is subjected to a two-step cooling process, as follows:
Step 1: cooling in stagnant air at 20°C with a convection coefficient of $10 \mathrm{W/m^2 \cdot K}$, until the center temperature reaches 335°C;
Step 2: cooling in a well-stirred water bath (with a convection coefficient of $6000 \mathrm{W/m^2 \cdot K}$) at 20°C, until the center temperature is 50°C.
Calculate the time required for each step. The material has a density of 3000 $\mathrm{kg/m^3}$, a conductivity of 20 $\mathrm{W/m \cdot K}$, a heat capacity of 1000 $\mathrm{J/kg \cdot K}$, and a thermal diffusivity of 6.65×10^{-6} $\mathrm{m^2/s}$.

Problem 3



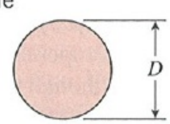
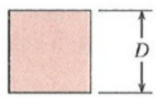
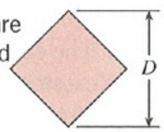
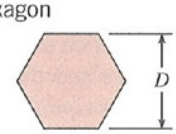
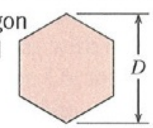
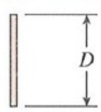
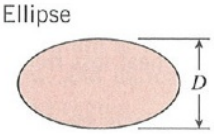
A radiant space heater consists of a long, diffuse, gray, cylindrical heating element that is of diameter D= 30 mm, and is backed by a curved metallic reflector. The surface temperature and emissivity of the heating element are T_1=945 K, and ε_1=0.8 respectively, and the temperature of the air and surrounding surfaces is 300 K. Convection heat transfer from the element is negligible. The reflector may be assumed to be an isothermal, diffuse gray surface with an emissivity ε_2=0.2, an arc length S= 0.3 m, and a width W= 0.15 m. The steady-state temperature of the reflector plate is T_2=385 K, and the view factor of the heater with respect to the reflector F_{12}=0.625.

Draw the radiant circuit which describes radiation heat transfer between the reflector, heating element and surroundings. For a unit length of the heater, evaluate all resistances and known nodal potentials. Finally, calculate the electrical power input to the heating element. Neglect the back of the reflector.

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m^3	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m^2/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Empirical correlations for the average Nusselt number for forced convection over circular and noncircular cylinders in cross flow (from Zukauskas, 1972 and Jakob, 1949)

Cross-section of the cylinder	Fluid	Range of Re	Nusselt number
Circle 	Gas or liquid	0.4–4 4–40 40–4000 4000–40,000 40,000–400,000	$Nu = 0.989Re^{0.330}\ Pr^{1/3}$ $Nu = 0.911Re^{0.385}\ Pr^{1/3}$ $Nu = 0.683Re^{0.466}\ Pr^{1/3}$ $Nu = 0.193Re^{0.618}\ Pr^{1/3}$ $Nu = 0.027Re^{0.805}\ Pr^{1/3}$
Square 	Gas	5000–100,000	$Nu = 0.102Re^{0.675}\ Pr^{1/3}$
Square (tilted 45°) 	Gas	5000–100,000	$Nu = 0.246Re^{0.588}\ Pr^{1/3}$
Hexagon 	Gas	5000–100,000	$Nu = 0.153Re^{0.638}\ Pr^{1/3}$
Hexagon (tilted 45°) 	Gas	5000–19,500 19,500–100,000	$Nu = 0.160Re^{0.638}\ Pr^{1/3}$ $Nu = 0.0385Re^{0.782}\ Pr^{1/3}$
Vertical plate 	Gas	4000–15,000	$Nu = 0.228Re^{0.731}\ Pr^{1/3}$
Ellipse 	Gas	2500–15,000	$Nu = 0.248Re^{0.612}\ Pr^{1/3}$

Summary of the solutions for one-dimensional transient conduction in a plane wall of thickness $2L$, a cylinder of radius r_o and a sphere of radius r_o subjected to convention from all surfaces.*

Geometry	Solution	λ_n's are the roots of
Plane wall	$\theta = \sum_{n=1}^{\infty} \frac{4 \sin \lambda_n}{2\lambda_n + \sin(2\lambda_n)} e^{-\lambda_n^2 \tau} \cos(\lambda_n x/L)$	$l_n \tan l_n$ 5 Bi
Cylinder	$\theta = \sum_{n=1}^{\infty} \frac{2}{\lambda_n} \frac{J_1(\lambda_n)}{J_0^2(\lambda_n) + J_1^2(\lambda_n)} e^{-\lambda_n^2 \tau} J_0(\lambda_n r/r_o)$	$\lambda_n \frac{J_1(\lambda_n)}{J_0(\lambda_n)} = \mathrm{Bi}$
Sphere	$\theta = \sum_{n=1}^{\infty} \frac{4(\sin \lambda_n - \lambda_n \cos \lambda_n)}{2\lambda_n - \sin(2\lambda_n)} e^{-\lambda_n^2 \tau} \frac{\sin(\lambda_n x/L)}{\lambda_n x/L}$	$1 - \lambda_n \cot \lambda_n = \mathrm{Bi}$

*Here $\theta = (T - T_\infty)/(T_i - T_\infty)$ is the dimensionless temperature, $\mathrm{Bi} = hL/k$ or hr_o/k is the Biot number, $\mathrm{Fo} = \tau = \alpha t/L^2$ or $\alpha\tau/r_o^2$ is the Fourier number, and J_0 and J_1 are the Bessel functions of the first kind whose values are given in Table 4–3.

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