# University of New Mexico
# Mechanical Engineering
# Fall 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. Three cylindrical rods of different radii and lengths can be used to connect two heat reservoirs at fixed temperatures $T_1$ and $T_2$ respectively. From the following pick out the rod which will conduct the maximum quantity of heat:

   (a) Radius 1 cm, length 1 m.

   (b) Radius 1 cm, length 2 m.

   (c) Radius 3 cm, length 8 m.

   Answer:

2. Which one of the following is not an example of convection?

   (a) Smoke rising above a fire.

   (b) A person gets suntan on a beach.

   (c) A chicken is cooked in water.

   Answer:

3. You sit next to a fireplace with a burning fire in it. There is a metal poker with one end stuck into the fire. Which statement describing the situation is definitely true?

   (a) You can feel the heat of the fire primarily due to convection.

   (b) Heat escapes through the chimney primarily via conduction.

   (c) The other end of the poker is warmed through conduction.

   Answer:

4. Equal masses of two liquids of specific heats $C_1$ and $C_2$ at temperatures $T_1$ and $T_2$ respectively are mixed. If there is no change of state, the temperature of the mixture is

   (a) $(T_1 + T_2)/2$.

   (b) $(C_1T_1 + C_2T_2)/[3(C_1 + C_2)]$.

   (c) $(C_1T_1 + C_2T_2)/(C_1 + C_2)$.

   Answer:

5. Heat transfer by convection will occur:

   (a) only in vacuum.

   (b) with or without the presence of a medium.

   (c) only in liquid, gas, or plasma.

   Answer:

6. 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:

7. Weather reporters often cite temperatures associated with a “wind chill” factor. This can be explained as:
   (a) The temperature in still air which would produce the same amount of heat loss as in the windy condition
   (b) The difference between the wet and dry bulb temperatures in humid air
   (c) The actual air temperature due to cold winds from the Arctic

   Answer:

8. Fins in most naturally convecting heat sinks for electronic devices are spaced about 7 mm apart, while fin spacing in heat sinks designed for forced convection varies greatly. This is because:
   (a) There is only one large manufacturer of extrusions used in naturally convecting fins
   (b) The optimum fin spacing is approximately 7 mm for natural convection at temperatures encountered in cooling of electronic devices
   (c) In forced convection optimum spacing is not critical, so manufacturers just use whatever fins are cheapest

   Answer:

9. 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:

10. Many thermally radiating / absorbing surfaces are dimpled or grooved. This is because:
    (a) The surface resistance is reduced
    (b) The configuration resistance is reduced
    (c) There is no heat transfer benefit, this is just done to enhance material stiffness

    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

A tent being considered for cold-weather conditions has insulation on the top and sides. The insulation has thermal conductivity $k = 0.041$ Wm$^{-1}$K$^{-1}$ and thickness $l = 0.50$ cm. A heater inside the tent is producing heat at a rate of 1500 W. The total surface area of the tent is 30 m$^2$. The characteristic heat transfer coefficient between the inside air and the tent surface is $h_i = 7$ Wm$^{-2}$K$^{-1}$, while the corresponding heat transfer coefficient between the outside air and outside tent surface is $h_o = 10$ Wm$^{-2}$K$^{-1}$. The outside temperature is $T_{ao} = 5$°C. Determine the temperature $T_{ai}$ inside the tent. State any simplifying assumptions.

**Problem 2**

Oranges are usually refrigerated as a preservative measure. However, some people prefer to eat oranges that are a little cooler than room temperature, but not as cold as the refrigerator makes them. Determine the time it takes so that the lowest temperature within an orange removed from a refrigerator is 20°C. Use the following conditions:

1. Refrigerated temperature = 4°C.
2. Ambient room temperature = 23°C.
3. Surface convection coefficient = 6 $\mathrm{Wm^{-2}K^{-1}}$.
4. Thermal conductivity of an orange = 0.431 $\mathrm{Wm^{-1}K^{-1}}$.
5. Density of orange = 0.998 kg $\mathrm{m^{-3}}$.
6. Specific heat of orange = 2 kJ $\mathrm{kg^{-1}K^{-1}}$.
7. Orange diameter = 105 mm.

Also, estimate the heat transferred by the ambient air to the orange during this time.

**Problem 3**

An automobile parked in the sun has a clear, polished plate-glass windshield approximately 6 mm thick. The car receives radiation in the amount of 1100 $\mathrm{Wm^{-2}}$ from the sun (assumed to be a black body at 5800 K). Calculate:

1. The rate at which the sun's radiant energy is transmitted through the glass windshield into the car.
2. The rate at which radiant energy from the car's interior is transmitted through the windshield to the outside, assuming that the interior of the car is a blackbody radiating at 38°C.

The average transmissivities for the ultraviolet (300nm to 380 nm), visible (380 nm to 720 nm) and infrared (720 nm to 2000 nm) ranges are 0.68, 0.88 and 0.67 respectively.

*Hint: consider the radiant fraction for the ultraviolet, visible and infrared separately.*

**Table 13.1** *Fraction of total radiation emitted over a given wavelength–temperature product.*

| $\lambda T \times 10^3$ m·K | $\dfrac{\int_0^{\lambda T} q''_{b\lambda}\, d\lambda}{\sigma T^4}$ | $\lambda T \times 10^3$ m·K | $\dfrac{\int_0^{\lambda T} q''_{b\lambda}\, d\lambda}{\sigma T^4}$ |
|---|---|---|---|
| 0.2 | $0.341796 \times 10^{-26}$ | 6.2 | 0.754187 |
| 0.4 | $0.186468 \times 10^{-11}$ | 6.4 | 0.769282 |
| 0.6 | $0.929299 \times 10^{-7}$ | 6.6 | 0.783248 |
| 0.8 | $0.164351 \times 10^{-4}$ | 6.8 | 0.796180 |
| 1.0 | $0.320780 \times 10^{-3}$ | 7.0 | 0.808160 |
| 1.2 | $0.213431 \times 10^{-2}$ | 7.2 | 0.819270 |
| 1.4 | $0.779084 \times 10^{-2}$ | 7.4 | 0.829580 |
| 1.6 | $0.197204 \times 10^{-1}$ | 7.6 | 0.839157 |
| 1.8 | $0.393449 \times 10^{-1}$ | 7.8 | 0.848060 |
| 2.0 | $0.667347 \times 10^{-1}$ | 8.0 | 0.856344 |
| 2.2 | 0.100897 | 8.5 | 0.874666 |
| 2.4 | 0.140268 | 9.0 | 0.890090 |
| 2.6 | 0.183135 | 9.5 | 0.903147 |
| 2.8 | 0.227908 | 10.0 | 0.914263 |
| 3.0 | 0.273252 | 10.5 | 0.923775 |
| 3.2 | 0.318124 | 11.0 | 0.931956 |
| 3.4 | 0.361760 | 11.5 | 0.939027 |
| 3.6 | 0.403633 | 12 | 0.945167 |
| 3.8 | 0.443411 | 13 | 0.955210 |
| 4.0 | 0.480907 | 14 | 0.962970 |
| 4.2 | 0.516046 | 15 | 0.969056 |
| 4.4 | 0.548830 | 16 | 0.973890 |
| 4.6 | 0.579316 | 18 | 0.980939 |
| 4.8 | 0.607597 | 20 | 0.985683 |
| 5.0 | 0.633786 | 25 | 0.992299 |
| 5.2 | 0.658011 | 30 | 0.995427 |
| 5.4 | 0.680402 | 40 | 0.998057 |
| 5.6 | 0.701090 | 50 | 0.999045 |
| 5.8 | 0.720203 | 75 | 0.999807 |
| 6.0 | 0.737864 | 100 | 1.000000 |

*Note:* Values from the $\lambda T$ column are read as follows:
$\lambda T \times 10^3$ m·K $= 0.2$; therefore $\lambda T = 0.2 \times 10^{-3}$ m·K.

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 | $\lambda_n$'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 | $\theta = \sum_{n=1}^{\infty} \frac{2}{\lambda_n} \frac{J_1(\lambda_n)}{J_0^2(\lambda_n) + J_1^2(\lambda_n)} e^{-\lambda_n^2 \tau} J_0(\lambda_n r/r_o)$ | $\lambda_n \frac{J_1(\lambda_n)}{J_0(\lambda_n)} = \text{Bi}$ |
| Sphere | $\theta = \sum_{n=1}^{\infty} \frac{4(\sin \lambda_n - \lambda_n \cos \lambda_n)}{2\lambda_n - \sin(2\lambda_n)} e^{-\lambda_n^2 \tau} \frac{\sin(\lambda_n x/L)}{\lambda_n x/L}$ | $1 - \lambda_n \cot \lambda_n = \text{Bi}$ |

*Here $\theta = (T - T_\infty)/(T_i - T_\infty)$ is the dimensionless temperature, Bi $= hL/k$ or $hr_o/k$ is the Biot number, 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** | $\lambda_1$ | $A_1$ | $\lambda_1$ | $A_1$ | $\lambda_1$ | $A_1$ |
| 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 |
| $\infty$ | 1.5708 | 1.2732 | 2.4048 | 1.6021 | 3.1416 | 2.0000 |