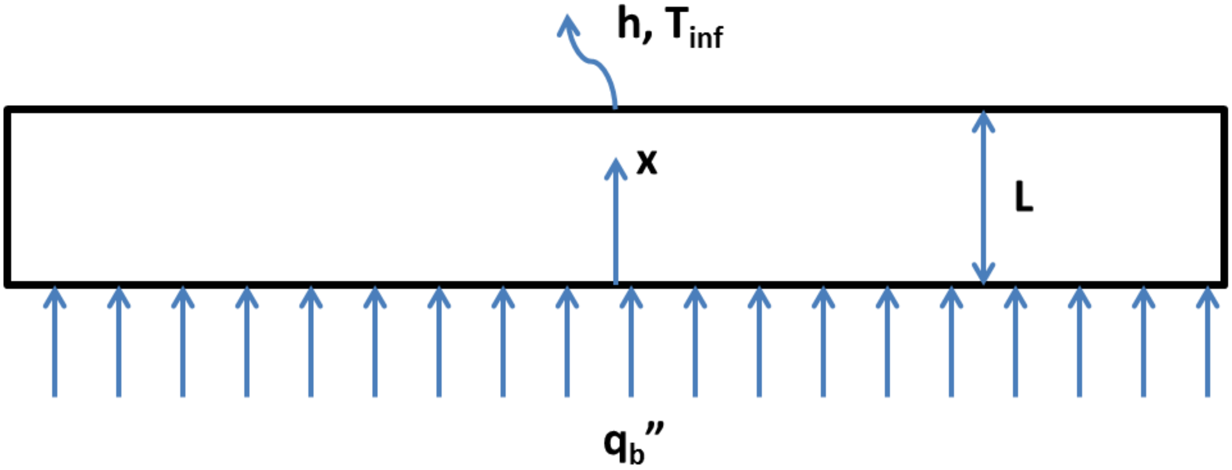
Ph.D. Qualifying Examination, Fall 2015

Heat Transfer

1. A hot plate of thickness L is initially at the ambient temperature T_{inf}. Starting from time t=0 the bottom of the plate is subjected to a heat flux q_b''. The upper surface is exposed to the ambient environment with an effective heat transfer coefficient of h. The thickness of the plate is small compared to its other dimensions, such that the heat loss from the sides may be neglected.



(i) **(30%)** Assuming the temperature to be ***uniform spatially within the plate*** at each instant, perform an energy balance to determine the governing equation and required conditions for the transient temperature variation. For a constant q_b'' determine the transient temperature variation T(t).

(ii) **(35%)** If the heat flux at the bottom surface oscillates as given by:

$q_b'' = q_0'' \text{ Cos } \omega t$

determine the transient temperature variation.

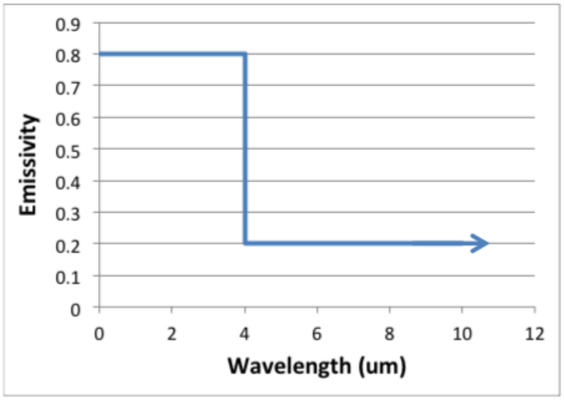
(iii) **(35%)** If the spatial temperature variation across the thickness is not negligible, write down the appropriate governing equations and conditions needed to determine the temperature variation T(x,t), due to a constant heat flux at the bottom surface, q_b''. Find the functional form of the solution T(x,t). What will be the temperature variation in steady state for a constant q_b'' ?

2. You are designing a closed loop plumbing system which includes two lines A and B of equal length in parallel. The diameters (I. D.) of the lines are 1" and 2" respectively.
   a. Determine the ratio of the mass flow rates in each of the lines. Assume that friction factor can be expressed as follows: $f = 0.316/\mathrm{Re}^{0.25}$.
   b. Assuming that the Dittus Boelter equation ($Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$) can be used for heat transfer, determine the ratio of the heat transfer coefficients in the two pipes.
   c. Determine the ratio of the rise in temperature of the fluid streams in the two pipes under a ***constant and equal imposed heat flux.***

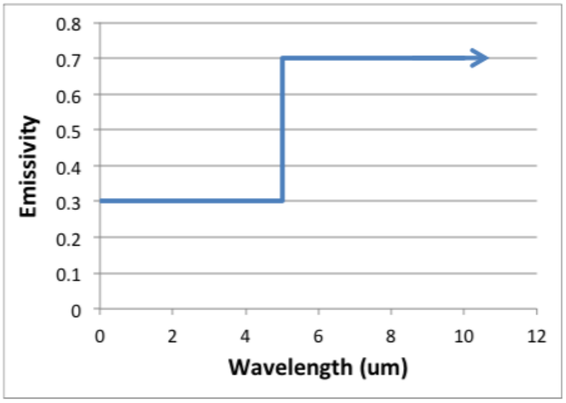
d. Recalculate your results for parts a-c if the flow in both pipes is laminar.

Steady state, constant fluid properties, and fully developed flow may be assumed in all cases.

3. A small diffuse opaque flat plate made of aluminum (initially at 300K) is put into a very large furnace with the walls at 1000K to be annealed. The square plate is 0.1 m on each side and 1 mm thick. The spectral emissivity of the plate and emissivity for the material for the walls of the furnace are shown below.



Emissivity of Plate



Emissivity of Furnace Walls

a) Determine the emissivity and absorptivity of the plate at 300 K.

b) A hot gas with properties similar to air at 700 K flows over the plate in the oven at 5 m/s. Determine the initial rate of heat transfer to the plate when it is first put into the oven, assuming that the air in the oven and the mounting for the plate does not interfere with the heat transfer exchange with the walls of the oven.

c) Estimate the steady state temperature of the plate.

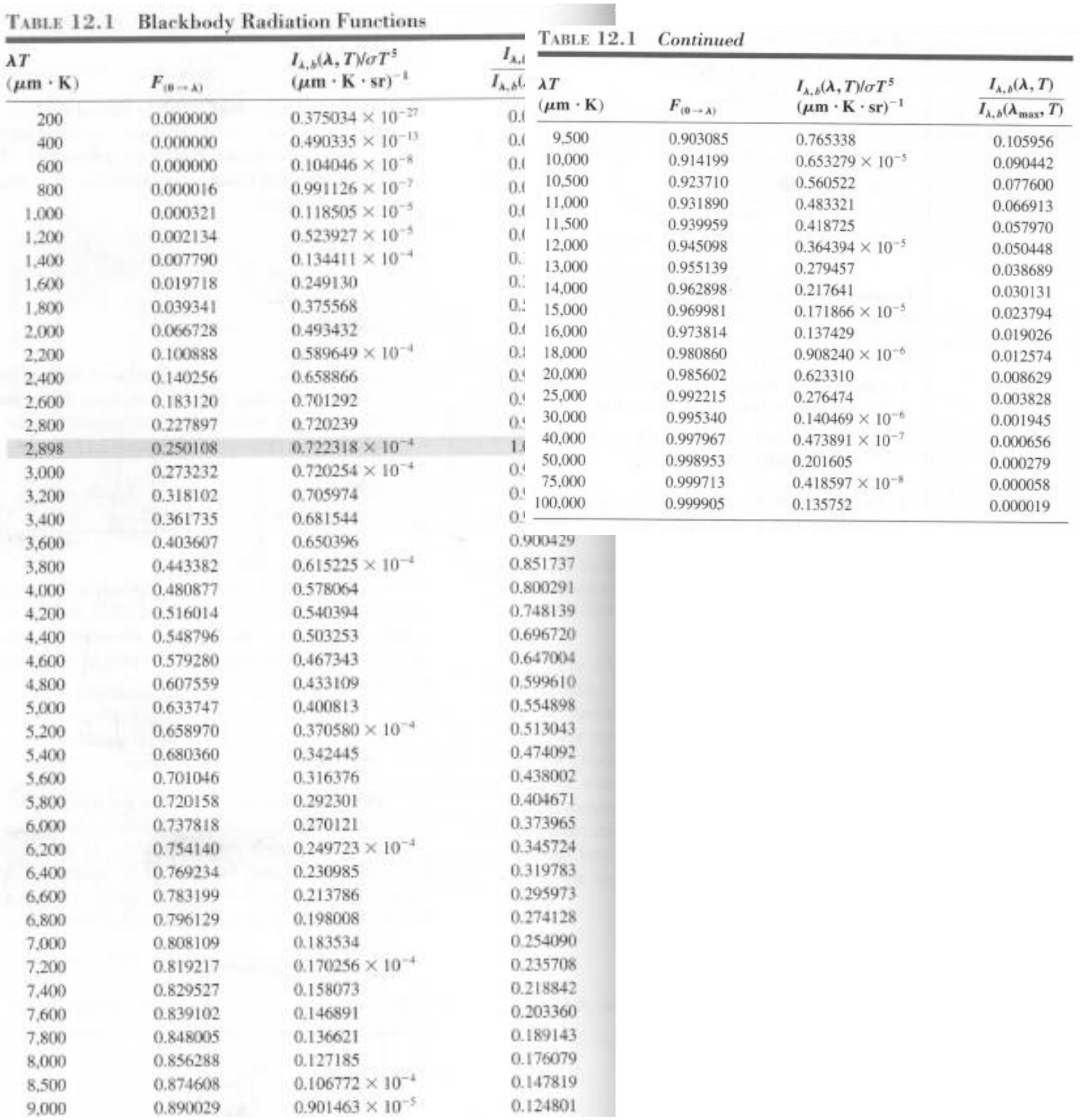


TABLE 12.1 Blackbody Radiation Functions

λT (μm · K)	$F_{(0\rightarrow\lambda)}$	$I_{\lambda,b}(\lambda,T)/\sigma T^5$ (μm · K · sr)$^{-1}$	$I_{\lambda,}$ / $I_{\lambda,b}$
200	0.000000	0.375034×10^{-27}	0.
400	0.000000	0.490335×10^{-13}	0.
600	0.000000	0.104046×10^{-8}	0.
800	0.000016	0.991126×10^{-7}	0.
1,000	0.000321	0.118505×10^{-5}	0.
1,200	0.002134	0.523927×10^{-5}	0.
1,400	0.007790	0.134411×10^{-4}	0.
1,600	0.019718	0.249130	0.
1,800	0.039341	0.375568	0.
2,000	0.066728	0.493432	0.
2,200	0.100888	0.589649×10^{-4}	0.
2,400	0.140256	0.658866	0.
2,600	0.183120	0.701292	0.
2,800	0.227897	0.720239	0.
2,898	0.250108	0.722318×10^{-4}	1.
3,000	0.273232	0.720254×10^{-4}	0.
3,200	0.318102	0.705974	0.
3,400	0.361735	0.681544	0.
3,600	0.403607	0.650396	0.900429
3,800	0.443382	0.615225×10^{-4}	0.851737
4,000	0.480877	0.578064	0.800291
4,200	0.516014	0.540394	0.748139
4,400	0.548796	0.503253	0.696720
4,600	0.579280	0.467343	0.647004
4,800	0.607559	0.433109	0.599610
5,000	0.633747	0.400813	0.554898
5,200	0.658970	0.370580×10^{-4}	0.513043
5,400	0.680360	0.342445	0.474092
5,600	0.701046	0.316376	0.438002
5,800	0.720158	0.292301	0.404671
6,000	0.737818	0.270121	0.373965
6,200	0.754140	0.249723×10^{-4}	0.345724
6,400	0.769234	0.230985	0.319783
6,600	0.783199	0.213786	0.295973
6,800	0.796129	0.198008	0.274128
7,000	0.808109	0.183534	0.254090
7,200	0.819217	0.170256×10^{-4}	0.235708
7,400	0.829527	0.158073	0.218842
7,600	0.839102	0.146891	0.203360
7,800	0.848005	0.136621	0.189143
8,000	0.856288	0.127185	0.176079
8,500	0.874608	0.106772×10^{-4}	0.147819
9,000	0.890029	0.901463×10^{-5}	0.124801

TABLE 12.1 *Continued*

λT (μm · K)	$F_{(0\rightarrow\lambda)}$	$I_{\lambda,b}(\lambda,T)/\sigma T^5$ (μm · K · sr)$^{-1}$	$\frac{I_{\lambda,b}(\lambda,T)}{I_{\lambda,b}(\lambda_{max},T)}$
9,500	0.903085	0.765338	0.105956
10,000	0.914199	0.653279×10^{-5}	0.090442
10,500	0.923710	0.560522	0.077600
11,000	0.931890	0.483321	0.066913
11,500	0.939959	0.418725	0.057970
12,000	0.945098	0.364394×10^{-5}	0.050448
13,000	0.955139	0.279457	0.038689
14,000	0.962898	0.217641	0.030131
15,000	0.969981	0.171866×10^{-5}	0.023794
16,000	0.973814	0.137429	0.019026
18,000	0.980860	0.908240×10^{-6}	0.012574
20,000	0.985602	0.623310	0.008629
25,000	0.992215	0.276474	0.003828
30,000	0.995340	0.140469×10^{-6}	0.001945
40,000	0.997967	0.473891×10^{-7}	0.000656
50,000	0.998953	0.201605	0.000279
75,000	0.999713	0.418597×10^{-8}	0.000058
100,000	0.999905	0.135752	0.000019

Flat Plate Correlations

Flow Conditions	Average Nusselt Number	Restrictions
Laminar	$\overline{Nu_L} = 0.664\,\mathrm{Re}_L^{1/2}\,\mathrm{Pr}^{1/3}$	$\mathrm{Pr} \geq 0.6$
Turbulent	$\overline{Nu_L} = \left(0.037\,\mathrm{Re}_L^{4/5} - A\right)\mathrm{Pr}^{1/3}$ where $A = 0.037\,\mathrm{Re}_{x,c}^{4/5} - 0.664\,\mathrm{Re}_{x,c}^{1/2}$	$0.6 \leq \mathrm{Pr} \leq 60$ $\mathrm{Re}_{x,c} \leq \mathrm{Re}_L \leq 10^8$