Marks scored:

KATHMANDU UNIVERSITY
End Semester Examination [C]
July, 2017

Level : B. E.
Year : III

Course : MEEG 306
Semester : I

Exam Roll No. :
Time: 30 mins.
F. M. : 20

Registration No.:
Date : JUL 14 2017

SECTION "A"
[20 Q. × 1 = 20 marks]

Cross [×] mark the most appropriate answer.

1. The heat flow through a 3 layered composite wall is given by ....
[ ] $Q = (T_1 - T_4)/[(1/A)(K_1/L_1 + K_2/L_2 + K_3/L_3)]$ [ ] $Q = (T_1 - T_4)/[A(K_1/L_1 + K_2/L_2 + K_3/L_3)]$
[ ] $Q = (T_1 - T_4)/[(1/A)(L_1/K_1 + L_2/K_2 + L_3/K_3)]$ [ ] $Q = (T_1 - T_4)/[A(L_1/K_1 + L_2/K_2 + L_3/K_3)]$

2. The conductivity of the metals .... with increase in temperature.
[ ] increases [ ] decreases [ ] remains constant [ ] unpredictable

3. Cork is a good insulator because............
[ ] its density is low [ ] it is porous [ ] it can be powdered [ ] it is a polymer

4. The steady state temperature distribution in a hollow cylinder when heat is flowing along the radius will be.................
[ ] linear [ ] parabolic [ ] hyperbolic [ ] logarithmic

5. Providing the fin to increase the heat transfer, the required condition is............
[ ] $(h.A/K.\rho)^{1/2} = 1$ [ ] $(h.A/K.\rho)^{1/2} > 1$
[ ] $(h.A/K.\rho)^{1/2} < 1$ [ ] $(h.A/K.\rho)^{1/2} > 1$ but <2

6. Effectiveness of a fin is not a direct function of ....
[ ] Thermal conductivity [ ] Surface or cross-sectional area
[ ] Temperature difference [ ] Convective heat transfer coefficient

7. Dropwise condensation occurs on a .... surface.
[ ] smooth [ ] oily [ ] coated [ ] glazed

8. A body at 100 °C is cooled to 80 °C in surrounding air at 30 °C in 12 minutes. The time taken to cool the same body from 80°C to 60°C in the same atmosphere will be ....
[ ] equal to 12 minutes [ ] < 12 minutes
[ ] > 12 minutes [ ] unpredictable

9. The Prandtl number for gases lies between ....
[ ] 0.65 to 1 [ ] 5 to 50 [ ] 60 to 100 [ ] 110 to 150

10. Film temperature is the .... of surface and ambient fluid temperature.
[ ] smaller [ ] larger [ ] difference [ ] average

11. For vertical plates, the critical Grashof number is ....

[ ] 10^3 [ ] 10^6 [ ] 10^9 [ ] 10^{12}

12. The characteristic length in case of vertical tube for natural convection is ....

[ ] diameter of tube [ ] perimeter of tube

[ ] height of the tube [ ] relative function of all three

13. Heat is lost from a steam pipe of 10 cm diameter to ambient air at 30°C. If the Nusselt number is 25 and K (air) = 0.03 W/mK, then the heat transfer coefficient on the surface of the pipe is ...... standard units.

[ ] 7.5 [ ] 16.25 [ ] 25.5 [ ] 30.2

14. For a fully developed laminar flow in a uniformly heated long circular tube, if the flow velocity is doubled and diameter is halved, the heat transfer coefficient will be ....

[ ] half of original [ ] same as before [ ] double of original [ ] 4 times of original

15. The average Nusselt number in a laminar natural convection from a vertical wall at 180°C when surrounding air temperature is 20°C is found to be 48. If the wall temperature falls to 30°C then the average Nusselt number will be ....

[ ] 8 [ ] 16 [ ] 24 [ ] 32

16. The fouling factor is ....

[ ] a dimensionless factor

[ ] used in the flow of Newtonian fluid

[ ] used to take into account the resistance formed by deposit

[ ] used exclusively in shell and tube heat exchangers

17. In a counter flow heat exchanger, the hot fluid is cooled from 140°C and 80°C and cold fluid is heated from 20°C to 80°C. The value of LMTD is ....

[ ] 110 [ ] 60 [ ] 50 [ ] indeterminate

18. The wavelength for maximum emissive power at a given temperature is given by ...... law.

[ ] Stefan-Boltzmann's [ ] Planck's

[ ] Wien's [ ] Kirchhoff's

19. A radiation shield should have ....

[ ] high emissivity [ ] low emissivity [ ] high reflectivity [ ] low reflectivity

20. Two concentric long cylinders with $D_2/D_1 = 5$, the shape factor of inner cylinder with itself will be ......

[ ] 0 [ ] 1/5 [ ] 4/5 [ ] 1

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F. M. : 55

SECTION "B"

Attempt ALL questions. Formula sheet is attached with the question paper; any extra data sheet is not allowed. Assume suitable data if necessary.

1.

a. The insulation boards for air conditioning purposes comprise three layers. A 12 cm thick layer of grass (k = 0.022 W/mK) is sandwiched between 3 cm thick layer of plywood (k = 0.15 W/mK) on each side. The bonding is achieved with glue which does not offer any resistance to heat flow. If the side surfaces of the board are maintained at 40°C and 20°C temperatures, determine the heat flux. How would the heat flux be affected if instead of glue, the three pieces are fastened by four steel bolts (k = 40 W/mK) of 1.2 cm diameter at the corners? Draw the resistive circuit diagram for the same. [6]

b. The following data pertains to a hollow cylinder and a hollow sphere made of the same material and having the same temperature drop over the wall thickness. The inside radius is 0.05 m and outside surface area is 1 m^2.If the outside radius of both the geometrics is same, calculate the ratio of heat flow in the cylinder to that in the sphere. What happens if the inside radius is doubled? [5]

2.

a. A rod of 10 mm square section and 160 mm length with thermal conductivity of 50 W/m°C protrudes from a furnace wall at 200°C, and is exposed to air at 30°C with convection coefficient 20 $W/m^{2o}C$. Make calculations for the heat convected up to 80 mm and 158 mm lengths and comment on the result. Adopt long fin model for the arrangement. [5]

b. A very long 25 mm diameter copper (k = 380 W/mK) rod extends from a surface at 120°C. The temperature of surrounding air is 25°C and the heat transfer coefficient over the rod is 10 W/m^2K. Calculate the heat loss from the rod. How long the rod should be in order to be considered infinite? (Perimeter for cylindrical rod = πd) [4]

c. Briefly explain fin effectiveness with suitable example. [2]

3.

a. Calculate the shape factors for the configurations shown in the figure given below [6]

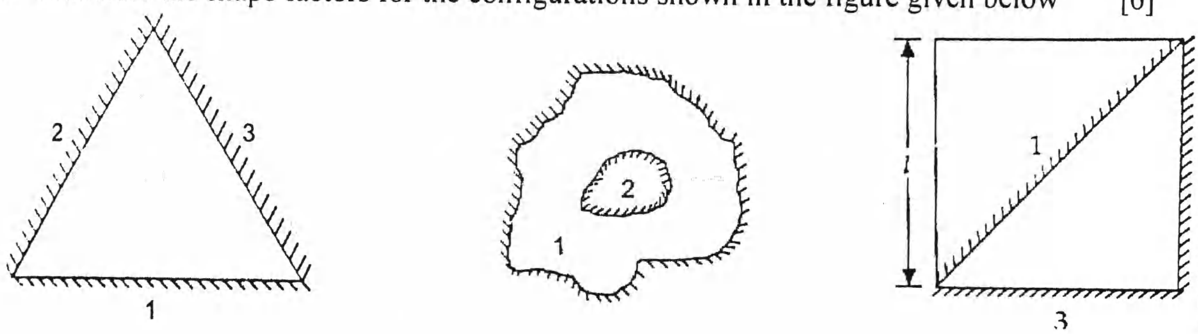

Figure 1

i. Long tube with cross section of an equilateral triangle
ii. Black body inside a black enclosure
iii. Diagonal partition within a long square duet

b. Two opposed, parallel, infinite planes are maintained at 420 K and 480 K respectively. Calculate the net heat flux between these planes if one has an emissivity of 0.8 and other an emissivity if 0.7. Does it matter which plate has which emissivity? How this heat flux will be affected if? [3]
   i. The temperature difference is doubled by raising the temperature 480 K to 540 K.
   ii. The planes are assumed to be black.

c. Explains Wien's displacement law with representative equations. [2]

4.

a. A heat exchanger is required to cool 55000 kg/h of alcohol from 66°C to 40°C using 40000 kg/h of water entering at 5°C. Taking overall heat transfer coefficient U = 580 W/m^2K, C_p (alcohol) = 3760 J/kgK, C_p (water) = 4180 J/kgK. Calculate exit temperature of water, heat transfer rate, surface area needed for parallel flow type and counter flow type exchanger. [5]

b. In a counter flow heat exchanger, hot fluid enters at 180°C and leaves at 118°C. The cold water enters at 99°C and leaves at 119°C. Find the LMTD and effectiveness. [3]

c. An industrial freezer is designed to operate with an internal air temperature of -20°C when the external air temperature is 25°C and the internal and external heat transfer coefficients are 12 W/m^2 K and 8 W/m^2 K, respectively. The walls of the freezer are composite construction, comprising of an inner layer of plastic (k = 1 W/m K, and thickness of 3 mm), and an outer layer of stainless steel (k = 16 W/m K, and thickness of 1 mm). Sandwiched between these two layers is a layer of insulation material with k = 0.07 W/M K. Find the width of the insulation that is required to reduce the convective heat loss to 15 W/m^2. [3]

5.

a. Air at 10°C and 100 kPa is flowing over a plate at 3 m/s. If the plate is 30 cm wide and at a temperature of 60°C. Calculate following quantities at x = 0.3 m. (The properties of air at 35°C is listed as: $\rho = 1.1373\ kg/m^3$, $\mu = 19 \times 10^{-6}$ kg/ms, $K_f = 0.0272$ W/m. K, Pr = 0.7 & $C_p = 1.006$ kJ/kg. K) [7]
   i. Boundary layer thickness,
   ii. Local friction coefficient,
   iii. Local shearing stress,
   iv. Total drag force,
   v. Thermal boundary layer thickness,
   vi. Local convective heat transfer coefficient,
   vii. The heat transfers from the plate.

b. A vertical plate of 20 cm height at 10°C is exposed to the atmospheric air. Find the heat flow per hour from the plate by natural convection from both sides. [4]
   Width of the plate = 10 cm
   Air temperature = 20 °C
   The local heat transfer coefficient for the vertical plate by natural convection is given by the following equation:

$$\frac{h_x}{K}x = Nu_x = 0.508\left[\frac{Pr}{0.952 + Pr}\right]^{1/4} (Gr_x Pr)^{1/4}$$

   The properties of air mean temperature of 60 °C are taken from the table as:
   $\rho = 1.06\ kg/m^3$, $C_p = 1008$ J/kg.K, K = 0.0285 W/m^2K
   $\mu = 20 \times 10^{-6}$ kg/m.s, $v = 18.97 \times 10^{-6}\ m^2/s$

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$Q = mc_p \Delta T = mc_p (T_2 - T_1)$	$\dot{q} = \dfrac{\dot{Q}}{A_s} \left[\dfrac{W}{m^2}\right]$
$\dot{Q}_{cond} = -kA_s \dfrac{dT}{dx}$ [W]	$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$ [W]
$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4)$ [W]	$R_{total} = \dfrac{\Delta T}{\dot{Q}} \left[\dfrac{K}{W}\right]$
$R_{wall} = \dfrac{L}{kA_s} \left[\dfrac{K}{W}\right]$	$R_{cyl} = \dfrac{\ln(r_2/r_1)}{2\pi Lk} \left[\dfrac{K}{W}\right]$
$R_{sph} = \dfrac{r_2 - r_1}{4\pi r_1 r_2 k} \left[\dfrac{K}{W}\right]$	$R_{rad} = \dfrac{1}{h_{rad} A_s} \left[\dfrac{K}{W}\right]$
$R_{conv} = \dfrac{1}{h A_s} \left[\dfrac{K}{W}\right]$	$h_{rad} = \dfrac{\dot{Q}_{rad}}{A_s(T_s - T_\infty)} = \varepsilon\sigma(T_s^2 + T_\infty^2)(T_s + T_\infty) \left[\dfrac{W}{m^2 K}\right]$
$r_{cr,\,cyl} = \dfrac{k_{ins}}{h}$ [m]	$r_{cr,\,sph} = \dfrac{2k_{ins}}{h}$ [m]
$\dfrac{\partial}{\partial x}\left\{\dfrac{\partial T}{\partial x}\right\} + \dfrac{g}{k} = \dfrac{1}{\alpha}\dfrac{\partial T}{\partial t}$	$\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{\partial T}{\partial r}\right) + \dfrac{g_0}{k} = \dfrac{1}{\alpha}\dfrac{\partial T}{\partial t} = \dfrac{\rho C}{k}\dfrac{\partial T}{\partial t}$
$Q = \dfrac{T_{\infty_1} - T_{\infty_2}}{\Sigma R_{th}}$;	$Q_{infinite\ fin} = \sqrt{hPkA_c}\,(T_0 - T_\infty)$
$m = \sqrt{\dfrac{hP}{kA_c}}$	$\dfrac{T(x) - T_\infty}{T_0 - T_\infty} = e^{-mx}$
$\dfrac{T_L - T_\infty}{T_0 - T_\infty} = \dfrac{1}{\cosh mL}$	$\dfrac{T - T_\infty}{T_0 - T_\infty} = \dfrac{\cosh m(L-x) + \frac{h}{mk}\sinh m(L-x)}{\cosh mL + \frac{h}{mk}\sinh mL}$
$Q_{fin} = \sqrt{hPkA_c}\,(T_0 - T_\infty) \times \dfrac{\sinh mL + \frac{h}{mk}\cosh mL}{\cosh mL + \frac{h}{mk}\sinh mL}$	$\eta_{fin} = \dfrac{\tanh mL}{mL}$
$\dot{Q}_{adi.\ tip} = \sqrt{hpkA_c}\,(T_b - T_\infty)\tanh mL$	$Q_{unfin} = hA_{unfin}(T_0 - T_\infty)$
$L_c = L + \dfrac{d}{4}$; for cylindrical fins	$L_c = L + \dfrac{t}{2}$; For longitudinal Straight fins
$A_c = w \times t$	$A_{unfin} = w\,(H - N_{fin}t)$
$\delta = \dfrac{5x}{\sqrt{Re_x}}$	$h = \dfrac{1}{x}\int_0^x h_x\,dx$
$Nu_x = \dfrac{h_x x}{k_f}$	$Re_x = \dfrac{\rho u_\infty x}{\mu}$
$Pr = \dfrac{\mu C_p}{k}$	$\tau_s = \mu \left.\dfrac{\partial u}{\partial y}\right\rvert_{y=0}$
$\tau_s = \dfrac{C_{fx}}{2}\rho u_\infty^2$	$C_{fx} = \dfrac{2\mu}{\rho u_\infty^2}\left.\dfrac{\partial u}{\partial y}\right\rvert_{y=0}$

$\varepsilon_{fin} = \frac{\dot{Q}_{fin}}{\dot{Q}_{no\ fin}} = \frac{\eta_{fin} h A_{fin}(T_b - T_\infty)}{h A_b (T_b - T_\infty)} = \eta_{fin} \frac{A_{fin}}{A_b}$	$Gr_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$; $\frac{g\rho^2\beta\Delta T L_c^3}{\mu^2}$
$Ra_L = Gr_L\ Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr$	$F_f = \frac{1}{2} C_f A_s \rho V^2$
$F_D = \frac{1}{2} C_D A_N \rho V^2$	$\delta_x = \frac{4.91x}{Re_x^{1/2}}$
$\tau_x = \frac{C_{fx}}{2} \rho u_\infty^2$	$\delta_{th} = \frac{\delta}{1.026} Pr^{-1/3}$
$\tau_s = 2\tau_x$, **Average shear stresss**	$h = 2h_x$, **Average heat transfer coefficient**
$C_{f,x} = \frac{0.664}{Re_x^{1/2}}$	$Nu_x = \frac{h_x x}{k} = 0.332 Re_x^{1/2} Pr^{1/3} \quad Pr > 0.6$
$Nu = \frac{hL}{k} = 0.664 Re_L^{1/2} Pr^{1/3}$	$C_f = \frac{1.33}{Re_L^{1/2}}$
$C_f = \frac{0.074}{Re_L^{1/5}} - \frac{1742}{Re_L}$ $5 \times 10^5 \le Re_L \le 10^7$	$Nu = \frac{hL}{k} = (0.037 Re_L^{4/5} - 871) Pr^{1/3}$ $0.6 \le Pr \le 60 \quad 5 \times 10^5 \le Re_L \le 10^7$
$Nu_{cyl} = \frac{hD}{k} = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{282{,}000}\right)^{5/8}\right]^{4/5}$	$Nu_{sph} = \frac{hD}{k} = 2 + \left[0.4 Re^{1/2} + 0.06 Re^{2/3}\right] Pr^{2/5} \left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$
$T_f = \frac{T_s + T_\infty}{2}$	$\dot{q}_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{c_{pl}(T_s - T_{sat})}{C_{sf} h_{fg} Pr_l^n}\right]^3$
$q_{max} = 0.149\, \rho_v^{1/2} h_{fg} [\sigma g(\rho - \rho_v)]^{1/4}$	$Q = \dot{m}_e h_{fg}$
$\dot{q}_{max} = C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4}$	$\dot{q}_{min} = 0.09 \rho_v h_{fg} \left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4}$
$\dot{q}_{rad} = \varepsilon\sigma (T_s^4 - T_{sat}^4)$	$\dot{q}_{film} = C_{film} \left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v)[h_{fg} + 0.4 c_{pv}(T_s - T_{sat})]}{\mu_v D (T_s - T_{sat})}\right]^{1/4} (T_s - T_{sat})$
$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4} \dot{q}_{rad}$	$Re = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 \rho_l V_l \delta}{\mu_l} = \frac{4\dot{m}}{p\mu_l}$
$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s)$	$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s) + c_{pv} (T_v - T_{sat})$
$\dot{Q}_{conden} = h A_s (T_{sat} - T_s) = \dot{m} h_{fg}^*$	$Re = \frac{4 \dot{Q}_{conden}}{p \mu_l h_{fg}^*} = \frac{4 A_s h (T_{sat} - T_s)}{p \mu_l h_{fg}^*}$

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$h_{vert} = 0.943 \left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg} k_l^3}{\mu_l (T_{sat} - T_s)L}\right]^{1/4}$	$Re \cong \frac{4g\rho_l(\rho_l - \rho_v)\delta^3}{3\mu_l^2} = \frac{4g\rho_l^2}{3\mu_l^2}\left(\frac{k_l}{h_{x=L}}\right)^3 = \frac{4g}{3\nu_l^2}\left(\frac{k_l}{3h_{vert}/4}\right)^3$
$h_{vert} \cong 1.47 k_l Re^{-1/3}\left(\frac{g}{\nu_l^2}\right)^{1/3}$	$h_{vert, wavy} = \frac{Re\, k_l}{1.08\, Re^{1.22} - 5.2}\left(\frac{g}{\nu_l^2}\right)^{1/3}$
$h_{vert, wavy} = 0.8\, Re^{0.11}\, h_{vert (smooth)}$	$Re_{vert, wavy} = \left[4.81 + \frac{3.70\, L k_l(T_{sat} - T_s)}{\mu_l h^*_{fg}}\left(\frac{g}{\nu_l^2}\right)^{1/3}\right]^{0.820}, \quad \rho_v \ll \rho_l$
$h_{inclined} = h_{vert}(\cos\theta)^{1/4}$ (laminar)	$h_{vert} = 0.943 \left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg} k_l^3}{\mu_l (T_{sat} - T_s)L}\right]^{1/4}$
$\frac{h_{vert}}{h_{horiz}} = 1.29\left(\frac{D}{L}\right)^{1/4}$	$h_{dropwise} = \begin{cases} 51{,}104 + 2044T_{sat}, \\ 255{,}310 \end{cases}$
$h = 0.725\left[\frac{\rho(\rho - \rho_v)\, g\, h_{fg}\, k_f^3}{\mu\, D\, (T_{sat} - T_s)}\right]^{1/4}$ **Horizontal tube**	$h = 1.13\left\{\frac{g\,\rho\,(\rho - \rho_v)\, h_{fg}\, k_f^3}{\mu\, L\,(T_{sat} - T_s)}\right\}^{1/4}$ **Vertical tube**
$\varepsilon_{parallel\ flow} = \frac{1 - \exp\left[-\frac{UA_s}{C_{min}}\left(1 + \frac{C_{min}}{C_{max}}\right)\right]}{1 + \frac{C_{min}}{C_{max}}}$	$\varepsilon_{parallel\ flow} = \frac{1 - \exp\left[-\frac{UA_s}{C_{min}}\left(1 + \frac{C_{min}}{C_{max}}\right)\right]}{1 + \frac{C_{min}}{C_{max}}}$
$NTU = \frac{UA_s}{C_{min}} = \frac{UA_s}{(\dot{m}c_p)_{min}}$	$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$
$q = \mu\, h_{fg}\left[\frac{g(\rho - \rho_v)}{\sigma}\right]^{1/2} \times \left[\frac{C_p \Delta T_e}{C_{sf}\, h_{fg}\, Pr^n}\right]^3$	$c = \frac{C_{min}}{C_{max}}$
$\varepsilon = \frac{1 - \exp[-NTU(1 + C)]}{1 + C}$	$\Sigma R_{th} = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(d_o/d_i)}{2\pi L k} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o}$
$\varepsilon_{counter} = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}}$	$\tau = \frac{\int_{\lambda_1}^{\lambda_2} \tau_\lambda E_{b\lambda}\, d\lambda}{\sigma T^4}$
$J = \varepsilon E_b + \rho G$	$G = \frac{J - \varepsilon E_b}{1 - \varepsilon}$
$Q_{net} = \frac{A\varepsilon(E_b - J)}{1 - \varepsilon}$	$Q_{net} = A(J - G)$
Rate of Energy Absorbed = αAG	$\lambda = \frac{c}{\nu}$
$e = h\nu = \frac{hc}{\lambda}$	$E_b(T) = \sigma T^4$ (W/m²)
$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]}$ (W/m² · μm)	$C_1 = 2\pi h c_0^2 = 3.74177 \times 10^8$ W · μm⁴/m² $C_2 = hc_0/k = 1.43878 \times 10^4$ μm · K

$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T)\, d\lambda = \sigma T^4$ (W/m²)	$E_{b,\,0\text{–}\lambda}(T) = \int_0^\lambda E_{b\lambda}(\lambda, T)\, d\lambda$ (W/m²)
$f_\lambda(T) = \dfrac{\int_0^\lambda E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4}$	$f_{\lambda_1-\lambda_2}(T) = f_{\lambda_2}(T) - f_{\lambda_1}(T)$
$G_{\text{abs}} = \alpha G = \alpha\sigma T^4$	$f_{\lambda_1-\lambda_2}(T) = \dfrac{\int_0^{\lambda_2} E_{b\lambda}(\lambda, T) d\lambda - \int_0^{\lambda_1} E_{b\lambda}(\lambda, T) d\lambda}{\sigma T^4} = f_{\lambda_2}(T) - f_{\lambda_1}(T)$
$G_{\text{sky}} = \sigma T_{\text{sky}}^4$ (W/m²)	$F_{j \to i} = F_{i \to j}$ when $A_i = A_j$ $F_{j \to i} \neq F_{i \to j}$ when $A_i \neq A_j$
$A_i F_{i \to j} = A_j F_{j \to i}$	$\sum_{j=1}^{N} F_{i \to j} = 1$
$F_{1 \to (2,3)} = F_{1 \to 2} + F_{1 \to 3}$	$J_i = E_{bi} = \sigma T_i^4$ (blackbody)
$\dot{Q}_{12,\text{ no shield}} = \dfrac{A\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$	$\dot{Q}_{12,\text{ one shield}} = \dfrac{E_{b1} - E_{b2}}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{13}} + \frac{1-\varepsilon_{3,1}}{A_3\varepsilon_{3,1}} + \frac{1-\varepsilon_{3,2}}{A_3\varepsilon_{3,2}} + \frac{1}{A_3 F_{32}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}}$
$\dot{Q}_{12,\,N\text{ shields}} = \dfrac{A\sigma(T_1^4 - T_2^4)}{(N+1)\left(\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1\right)} = \dfrac{1}{N+1}\dot{Q}_{12,\text{ no shield}}$	$\dot{q}_{\text{conv, to sensor}} = \dot{q}_{\text{rad, from sensor}}$ $h(T_f - T_{\text{th}}) = \varepsilon\sigma(T_{\text{th}}^4 - T_w^4)$