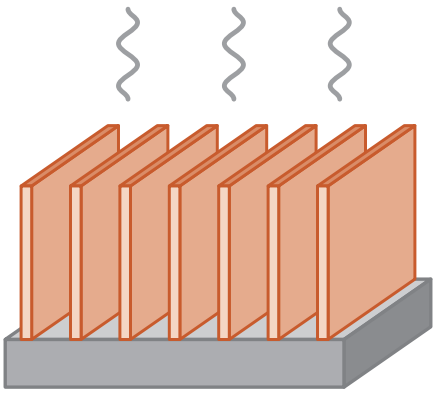
HEAT TRANSFER

PROBLEM BOOK

SAMPLE PAGES

14 chapters · 180 problems · step-by-step solutions



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How to use this book

- Each chapter opens with a reminder box summarizing the definitions and formulas the problems rely on.
- Difficulty: ★☆☆ basic ★★☆ intermediate ★★★ advanced. Each chapter has a few multiple-choice concept questions; its last problem is an exam-style mixed problem combining several topics.
- The dotted area below each problem is for your own work. Solve first; if stuck, go back to the reminder box and the lecture notes, and look at the solution last.
- All solutions are at the end of the book. The Solution → link next to a problem takes you to its solution, and ← Problem takes you back. Short answers are in the **ANSWER** box. Each solution begins with its assumptions and states the temperature at which the properties are evaluated.
- **Appendix tables:** Fluid and solid properties, transient conduction coefficients, Bessel functions, the blackbody radiation function, emissivities, convection correlations, heat exchanger relations, and view factors are in the appendices. The problems are solved with these appendices and the data in the problem statement only; values between table entries are found by linear interpolation.
- **Advanced chapters: 5 and 11.** Two-dimensional conduction and finite differences (Chapter 5) and boiling and condensation (Chapter 11) are covered in about half of the courses; they are marked ADVANCED in the contents. If your course does not cover these topics, you can skip these two chapters; the later chapters do not depend on them.
- **Midterm and final:** Choose the chapters according to your own syllabus. Courses that teach radiation before convection can study Chapters 13–14 before Chapter 7. All problems are in SI units.

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CHAPTER 2

THE HEAT CONDUCTION EQUATION

plane wall	$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\dot{e}_{\text{gen}}=\rho c_p\frac{\partial T}{\partial t}$	specified temperature	$T(0,t)=T_1$
constant k	$\frac{\partial^2 T}{\partial x^2}+\frac{\dot{e}_{\text{gen}}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$	specified heat flux	$-k\frac{\partial T(0,t)}{\partial x}=\dot{q}_0$
cylinder	$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\dot{e}_{\text{gen}}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$	insulated, symmetry	$\frac{\partial T(0,t)}{\partial x}=0$
sphere	$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\frac{\dot{e}_{\text{gen}}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$	convection ($x=L$)	$-k\frac{\partial T(L,t)}{\partial x}=h\left[T(L,t)-T_\infty\right]$
variable k	$k=k_0(1+\beta T):\ \dot{q}=k_{\text{avg}}\frac{T_1-T_2}{L}$	interface	$T_A=T_B,\quad k_A\frac{\partial T_A}{\partial x}=k_B\frac{\partial T_B}{\partial x}$
		initial condition	$T(x,0)=T_i(x)$

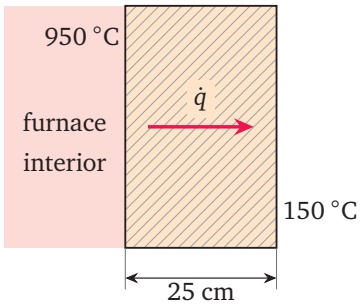
In the convection and radiation boundary conditions, the flux arriving at the surface by conduction equals the flux leaving the surface to the fluid and the surroundings; for radiation the term $\varepsilon\sigma[T(L)^4-T_{\text{surr}}^4]$ is added. The direction of the x axis fixes the signs: if a fluid touches the face at $x=0$ from the left, the condition there is $-k\,\partial T/\partial x=h[T_\infty-T(0)]$. In the relation for variable k, $k_{\text{avg}}=k_0[1+\beta(T_1+T_2)/2]$. At steady state the time-dependent term is zero.

Solution of steady one-dimensional problems

2.6

★★☆ Solution →

The inner face of the 25 cm thick fireclay brick wall of a heat treatment furnace is at 950 °C and its outer face at 150 °C. The thermal conductivity of the brick varies linearly with temperature: $k=0.90(1+5.0\times10^{-4}\,T)$ W/(m·K) (T in °C). Heat conduction is steady and one-dimensional; there is no heat generation.



a. Find the heat flux through the wall.

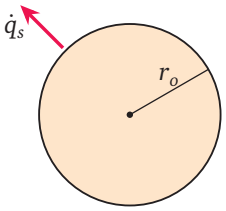
b. By solving the heat conduction equation, find the temperature at the middle of the wall. Why does it differ from 550 °C?

c. If the thermal conductivity were taken constant at its 25 °C value, by what percentage would the flux be in error?

Mixed problems

2.10

★★★ Solution →



sphere section

In a chemical reactor, an exothermic reaction inside porous spherical catalyst pellets 8 mm in diameter generates heat uniformly at $\dot{e}_{\text{gen}} = 4.0 \times 10^6\ \text{W/m}^3$. The effective thermal conductivity of a pellet is 0.40 W/(m·K). The pellets exchange heat with gas at 250 °C with a coefficient of $h = 150\ \text{W/(m}^2\text{·K)}$. Heat conduction is steady and radial.

a. By solving the heat conduction equation in spherical coordinates with its boundary conditions, find the temperature distribution in the pellet.

b. Find the surface and center temperatures of the pellet.

c. To avoid damaging the catalyst, the center temperature must not exceed 320 °C. Under the same conditions, what is the largest allowable pellet diameter in mm?

CHAPTER 3

STEADY ONE-DIMENSIONAL HEAT CONDUCTION

plane wall $R_{\text{wall}} = \dfrac{L}{kA}$

cylindrical layer $R_{\text{cyl}} = \dfrac{\ln(r_2/r_1)}{2\pi kL}$

spherical layer $R_{\text{sph}} = \dfrac{r_2 - r_1}{4\pi k\, r_1 r_2}$

convection $R_{\text{conv}} = \dfrac{1}{hA}$

radiation $R_{\text{rad}} = \dfrac{1}{h_{\text{rad}} A}$

$$h_{\text{rad}} = \varepsilon\sigma\,(T_s^2 + T_{\text{surr}}^2)(T_s + T_{\text{surr}})$$

contact $R_c = \dfrac{R_A}{A}$

series $\dot{Q} = \dfrac{T_{\infty,1} - T_{\infty,2}}{R_{\text{tot}}}, \quad R_{\text{tot}} = \sum R_i$

parallel $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \cdots$

overall heat transfer coefficient $UA = \dfrac{1}{R_{\text{tot}}}$

critical radius

$r_{\text{cr}} = \dfrac{k}{h}$ (cylinder), $\quad r_{\text{cr}} = \dfrac{2k}{h}$ (sphere)

wall with generation

$$T_0 - T_s = \frac{\dot{e}_{\text{gen}} L^2}{2k}, \quad T_s = T_\infty + \frac{\dot{e}_{\text{gen}} L}{h}$$

cylinder with generation

$$T_0 - T_s = \frac{\dot{e}_{\text{gen}} r_o^2}{4k}, \quad T_s = T_\infty + \frac{\dot{e}_{\text{gen}} r_o}{2h}$$

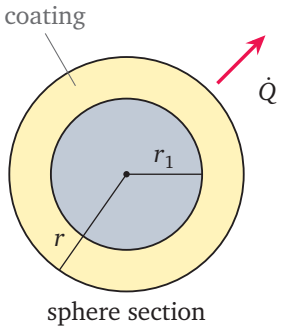
Resistances are in K/W. R_A is the resistance per 1 m^2 (m^2·K/W); dividing by the area gives $R = R_A/A$. In the radiation coefficient the temperatures are in kelvins; T_{surr} is the temperature of the surrounding surfaces, and the convection and radiation resistances of the same surface are connected in parallel. In a series circuit the temperature drop across each resistance is $\dot{Q}R$. For the plane wall with heat generation, L is the half-thickness and T_0 the midplane temperature; for the cylinder, r_o is the outer radius and T_0 the centerline temperature; in both relations the whole surface is exposed to the same fluid at T_∞. Adding a thin layer of insulation to a cylinder or sphere whose outer radius is smaller than r_{cr} increases the heat loss.

Critical radius of insulation

3.12

★★☆ Solution →

The surface of a sphere with a radius of 2 cm is kept at 80 °C by a heater inside it. The sphere loses heat to air at 20 °C with a combined heat transfer coefficient of $h = 16\ \text{W/(m}^2\cdot\text{K)}$. The sphere is to be coated with a material whose thermal conductivity is $0.24\ \text{W/(m}\cdot\text{K)}$; the same h applies on the outer surface of the coating, and the surface temperature of the sphere does not change.



sphere section

a. Find the heat loss of the uncoated sphere and the critical radius for the coating.

b. If the outer radius of the coating equals the critical radius, what is the heat loss? By what percentage does it increase relative to the uncoated sphere?

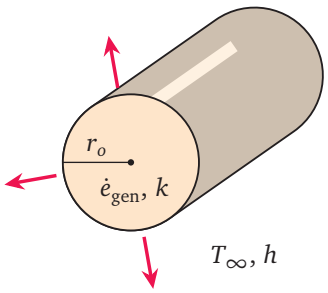
c. For the same sphere, the coating must not increase the heat loss at any thickness. What is the largest allowable thermal conductivity of the coating material?

Conduction with heat generation

3.14

★★☆ Solution →

Heat is generated uniformly at a rate of 3×10^6 W/m^3 in a long solid cylinder whose thermal conductivity is 1.5 W/(m·K). The cylinder is cooled by a fluid at 25 °C with $h = 500$ W/(m^2·K). The temperature must not exceed 175 °C anywhere in the material.



a. What is the largest allowable diameter of the cylinder?

b. For this diameter, find the surface temperature and the heat transfer rate per unit length.

c. If the diameter is taken as half of the value in part a, what is the maximum temperature?

CHAPTER 14

RADIATION EXCHANGE BETWEEN SURFACES

reciprocity	$A_iF_{ij} = A_jF_{ji}$	parallel plates	$\dot{q} = \dfrac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$
summation rule	$\sum_j F_{ij} = 1$	concentric cylinders	$\dot{Q} = \dfrac{A_1\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + (1/\varepsilon_2 - 1)r_1/r_2}$
crossed strings	$F_{12} = \dfrac{\sum\text{crossed} - \sum\text{uncrossed}}{2L_1}$	concentric spheres	$\dfrac{r_1}{r_2} \to \left(\dfrac{r_1}{r_2}\right)^2$
black surfaces	$\dot{Q}_{12} = A_1F_{12}\,\sigma(T_1^4 - T_2^4)$	small body, large enclosure	$\dot{Q} = \varepsilon_1 A_1 \sigma(T_1^4 - T_2^4)$
surface resistance	$\dfrac{1-\varepsilon_i}{A_i\varepsilon_i}, \quad \dot{Q}_i = \dfrac{E_{bi} - J_i}{(1-\varepsilon_i)/(A_i\varepsilon_i)}$	reradiating surface	$\dot{Q}_R = 0, \quad J_R = E_{bR}$
space resistance	$\dfrac{1}{A_iF_{ij}}, \quad \dot{Q}_{ij} = A_iF_{ij}(J_i - J_j)$	N equal shields	$\dot{Q}_N = \dfrac{\dot{Q}_0}{N+1}$

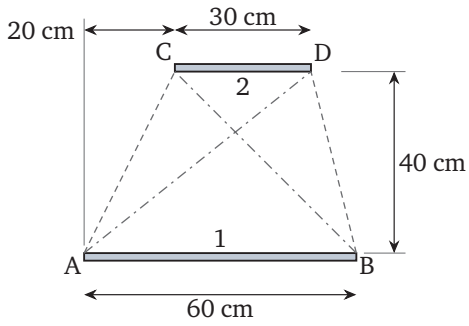
The view factor relations are in Table G-1 and the emissivities in Table D-2. Unless stated otherwise, surfaces are opaque, diffuse, gray, and isothermal, and the medium between them does not absorb radiation. In the radiation network, $E_b = \sigma T^4$ (temperature in kelvins) and the radiosity J act as potentials and $\dot{Q}$ as the current; in the formula for N shields all surfaces have the same emissivity. Large surroundings or an opening are treated as a black surface at the surroundings temperature.

The view factor

14.4

★★☆ Solution →

The two long strips whose cross section is shown are parallel to each other. Strip 1 (AB) is 60 cm wide; strip 2 (CD) is 30 cm wide and lies 40 cm above strip 1; point C is 20 cm in from A horizontally. The strips are very long in the direction normal to the page.



a. Find F_{12} by the crossed-strings method.

b. What is F_{21}?

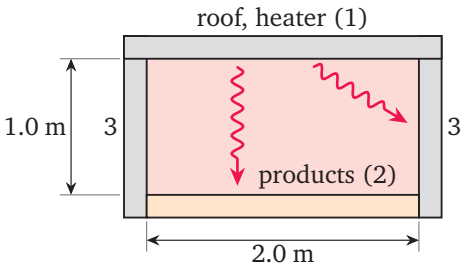
c. What percentage of the radiation from the facing sides of the two strips goes to the surroundings?

Radiation exchange between black surfaces

14.6

★★☆ Solution →

The cross section of a long, continuously operating tunnel furnace is a rectangle 2.0 m wide and 1.0 m high. Heaters in the roof keep the roof surface (1) at 1200 K; the products covering the floor (2) are at 520 K; the two side walls (3) are at 900 K. Treat all surfaces as black; for a 1 m section of the furnace:



a. Find the view factors from the roof to the floor and from the roof to the side walls.

b. Find the net heat given off by the roof by radiation and the net heat received by the products.

c. If the temperature of the side walls stays constant, how much heat passes through the walls to the outside?

SOLUTIONS

2 THE HEAT CONDUCTION EQUATION

2.6

← Problem

Assumptions: steady, one-dimensional conduction; no generation; $k(T)$ as given.

a. Since $\frac{d}{dx}(k\frac{dT}{dx}) = 0$, $\dot{q} = -k\,dT/dx$ is constant; integrating from 0 to L:

$$\dot{q}L = \int_{T_2}^{T_1} k\,dT = k_{\text{avg}}(T_1 - T_2)$$

$$k_{\text{avg}} = 0.90\big[1 + 5.0\times10^{-4}(550)\big] = 1.1475\ \text{W/(m·K)}$$

$$\dot{q} = \frac{1.1475(800)}{0.25} = 3672\ \text{W/m}^2$$

b. Integrating from 0 to x, with $F(T) = T + \frac{\beta}{2}T^2$:

$$F(T) = F(T_1) - \big[F(T_1) - F(T_2)\big]\frac{x}{L}$$

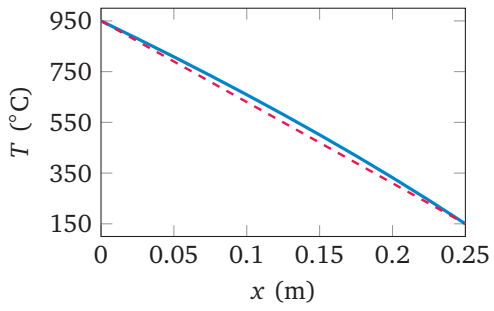
$$F(950) = 1175.6, \quad F(150) = 155.6$$

At the middle ($x = L/2$), $F = 665.6$:

$$2.5\times10^{-4}\,T^2 + T - 665.6 = 0$$

$$T = \frac{-1 + \sqrt{1 + 4(2.5\times10^{-4})(665.6)}}{2(2.5\times10^{-4})} = 581.2\ ^\circ\text{C}$$

Since the flux is constant, the gradient is inversely proportional to k: on the hot side k is large (1.328) and the gradient small; on the cold side k is small (0.968 W/(m·K)) and the gradient large. The profile is not linear, and its middle lies above the linear value (550 °C).



(Blue: actual profile; red dashed: linear profile with constant k.)

c. $k(25) = 0.90[1 + 5.0\times10^{-4}(25)] = 0.9113$ W/(m·K):

$$\dot{q} = \frac{0.9113(800)}{0.25} = 2916\ \text{W/m}^2$$

The flux would be underestimated by $1 - 2916/3672 = 0.206$, that is, 20.6%.

ANSWER **a.** 3672 W/m² **b.** 581.2 °C **c.** 20.6% low

2.10

← Problem

Assumptions: steady, radial conduction; uniform heat generation; constant k and h; radiation neglected.

a. Equation and boundary conditions:

$$\frac{1}{r^2}\frac{d}{dr}\Big(r^2\frac{dT}{dr}\Big) = -\frac{\dot{e}_{\text{gen}}}{k}$$

$$\frac{dT(0)}{dr} = 0, \qquad -k\frac{dT(r_o)}{dr} = h\big[T(r_o) - T_\infty\big]$$

Integrating once; a finite (zero) gradient at the center makes the constant zero:

$$\frac{dT}{dr} = -\frac{\dot{e}_{\text{gen}}\,r}{3k}$$

From the surface condition, $T_s = T_\infty + \dot{e}_{\text{gen}} r_o/(3h)$; the second integral gives

$$T(r) = T_\infty + \frac{\dot{e}_{\text{gen}} r_o}{3h} + \frac{\dot{e}_{\text{gen}}}{6k}(r_o^2 - r^2)$$

b. $r_o = 0.004$ m:

$$T_s = 250 + \frac{4.0\times10^6(0.004)}{3(150)} = 285.6\ ^\circ\text{C}$$

$$T(0) - T_s = \frac{4.0\times10^6(0.004)^2}{6(0.40)} = 26.67\ ^\circ\text{C}$$

$$T(0) = 285.6 + 26.67 = 312.2\ ^\circ\text{C}$$

The surface flux is $\dot{e}_{\text{gen}} r_o/3 = 5333\ \text{W/m}^2$.

c. The condition $T(0) - T_\infty = 70$ °C is a quadratic equation in r_o:

$$\frac{\dot{e}_{\text{gen}}}{6k}r_o^2 + \frac{\dot{e}_{\text{gen}}}{3h}r_o - 70 = 0$$

$$1.667\times10^6\,r_o^2 + 8889\,r_o - 70 = 0$$

$$r_o = \frac{-8889 + \sqrt{8889^2 + 4(1.667\times10^6)(70)}}{2(1.667\times10^6)}$$

$$r_o = 4.341\times10^{-3}\ \text{m}, \qquad D = 8.68\ \text{mm}$$

In a larger pellet the heat generated grows with the

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volume (r_o^3), whereas the surface through which it leaves grows with r_o^2; therefore the center temperature rises rapidly with diameter.

ANSWER **a.** $T(r) = T_\infty + \frac{\dot{e}_{\text{gen}} r_o}{3h} + \frac{\dot{e}_{\text{gen}}}{6k}(r_o^2 - r^2)$ **b.** $T_s = 285.6\ ^\circ\text{C}$, $T(0) = 312.2\ ^\circ\text{C}$ **c.** 8.68 mm

3 STEADY ONE-DIMENSIONAL HEAT CONDUCTION

3.12

← Problem

Assumptions: steady, radial conduction; constant properties; no contact resistance between the coating and the sphere; h includes radiation and is not affected by the coating.

a. Uncoated sphere:

$$\dot{Q}_0 = h(4\pi r_1^2)(T_s - T_\infty)$$

$$\dot{Q}_0 = 16(4\pi)(0.02)^2(60) = 4.825\ \text{W}$$

$$r_{\text{cr}} = \frac{2k}{h} = \frac{2(0.24)}{16} = 0.030\ \text{m} = 30\ \text{mm}.$$

Since $r_1 = 20\ \text{mm} < r_{\text{cr}}$, a thin coating increases the loss.

b. Resistances for $r = 0.030$ m (K/W):

$$R_{\text{coat}} = \frac{1/0.02 - 1/0.03}{4\pi(0.24)} = 5.526$$

$$R_{\text{conv}} = \frac{1}{16(4\pi)(0.03)^2} = 5.526$$

$$\dot{Q} = \frac{60}{11.052} = 5.429\ \text{W}, \qquad \frac{5.429}{4.825} = 1.125$$

The loss increases by 12.5%; this is the largest loss that can be reached with a coating.

c. The total resistance increases with the outer radius for $r > r_{\text{cr}}$ and decreases for $r < r_{\text{cr}}$. For the coating not to increase the loss at any thickness, the radius of the sphere must not be smaller than the critical radius:

$$r_1 \geq r_{\text{cr}} = \frac{2k}{h} \Rightarrow k \leq \frac{hr_1}{2}$$

$$k \leq \frac{16(0.02)}{2} = 0.16\ \text{W/(m·K)}.$$

At this value $r_{\text{cr}} = r_1 = 20$ mm; any coating increases the total resistance. With the given material of $k = 0.24$ W/(m·K), on the other hand, the loss falls below the uncoated value only when the coating is thicker than 40 mm ($r = 60$ mm from $1/r = h/k - 1/r_1$).

ANSWER **a.** $\dot{Q}_0 = 4.825$ W, $r_{\text{cr}} = 30$ mm **b.** 5.429 W, 12.5% **c.** $k \leq 0.16$ W/(m·K)

3.14

← Problem

Assumptions: steady, radial (one-dimensional) conduction; constant k; uniform heat generation. The maximum temperature is at the centerline (T_0).

a. The surface energy balance $h(2\pi r_o)(T_s - T_\infty) = \dot{e}_{\text{gen}} \pi r_o^2$ together with the difference inside the cylinder:

$$T_0 - T_\infty = \frac{\dot{e}_{\text{gen}} r_o}{2h} + \frac{\dot{e}_{\text{gen}} r_o^2}{4k}.$$

With $\dot{e}_{\text{gen}}/(2h) = 3000$ K/m, $\dot{e}_{\text{gen}}/(4k) = 5.0 \times 10^5$ K/m^2, and $T_0 - T_\infty = 150$ K:

$$5.0 \times 10^5 r_o^2 + 3000 r_o - 150 = 0$$

$$r_o = \frac{-3000 + \sqrt{3000^2 + 4(5.0 \times 10^5)(150)}}{2(5.0 \times 10^5)}$$

$$r_o = \frac{-3000 + 17\,578}{10^6} = 0.01458\ \text{m}.$$

The largest diameter is $D = 2r_o = 29.2$ mm.

b. Surface temperature and heat transfer rate per unit length:

$$T_s = 25 + 3000(0.01458) = 68.7\ ^\circ\text{C}$$

$$\dot{Q}/L = \dot{e}_{\text{gen}} \pi r_o^2 = 3 \times 10^6 \pi (0.01458)^2 = 2003\ \text{W/m}.$$

Check: $T_0 - T_s = 5.0 \times 10^5 (0.01458)^2 = 106.3$ K; $68.7 + 106.3 = 175\ ^\circ\text{C}$.

c. $r_o = 0.00729$ m:

$$T_0 = 25 + 3000(0.00729) + 5.0 \times 10^5 (0.00729)^2$$

$$T_0 = 25 + 21.87 + 26.57 = 73.4\ ^\circ\text{C}.$$

When the diameter is halved, the convection difference is halved and the internal difference drops to a quarter; the maximum temperature falls from 175 °C to 73.4 °C.

ANSWER **a.** $D = 29.2$ mm **b.** $T_s = 68.7\ ^\circ\text{C}$, $\dot{Q}/L = 2003$ W/m **c.** $T_0 = 73.4\ ^\circ\text{C}$

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14 RADIATION EXCHANGE BETWEEN SURFACES

14.4

← Problem

Assumptions: two-dimensional (infinitely long) geometry; the strips are flat.

a. String lengths (cm):

$$AC = \sqrt{20^2 + 40^2} = 44.72$$

$$BD = \sqrt{10^2 + 40^2} = 41.23$$

$$AD = \sqrt{50^2 + 40^2} = 64.03$$

$$BC = \sqrt{40^2 + 40^2} = 56.57$$

The crossed strings are AD and BC, the uncrossed ones AC and BD:

$$F_{12} = \frac{(64.03 + 56.57) - (44.72 + 41.23)}{2(60)} = 0.2887$$

b. Per unit length, $A_1 = 0.60$ and $A_2 = 0.30$:

$$F_{21} = \frac{0.60}{0.30}(0.2887) = 0.5775$$

c. The strips are flat; the part that does not reach the other strip goes to the surroundings:

$$F_{1\to\text{surr}} = 1 - 0.2887 = 0.7113$$

$$F_{2\to\text{surr}} = 1 - 0.5775 = 0.4225$$

71.1% of the radiation of strip 1 and 42.3% of that of strip 2 go to the surroundings.

ANSWER **a.** $F_{12} = 0.2887$ **b.** $F_{21} = 0.5775$ **c.** 71.1%; 42.3%

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14.6

← Problem

Assumptions: black, isothermal surfaces; two-dimensional geometry (long furnace, no end effects); the gases do not absorb radiation.

a. Crossed-strings method: the crossed strings are the two diagonals ($\sqrt{5} = 2.236$ m), the uncrossed ones the two side walls (1 m):

$$F_{12} = \frac{2(2.236) - 2(1)}{2(2)} = 0.6180, \qquad F_{13} = 0.3820$$

b. $E_{b1} = 117\,573$, $E_{b2} = 4146$, $E_{b3} = 37\,201$ W/m^2; $A_1 = A_2 = 2$ m^2, $A_3 = 2$ m^2 (two walls):

$$\dot{Q}_{12} = 2(0.6180)(117\,573 - 4146) = 1.402 \times 10^5 \text{ W}$$

$$\dot{Q}_{13} = 2(0.3820)(117\,573 - 37\,201) = 6.140 \times 10^4 \text{ W}$$

$$\dot{Q}_1 = 2.016 \times 10^5 \text{ W}$$

By symmetry, $A_3F_{32} = A_2F_{23} = A_1F_{13}$:

$$\dot{Q}_{32} = 2(0.3820)(37\,201 - 4146) = 2.525 \times 10^4 \text{ W}$$

$$\dot{Q}_2 = 1.402 \times 10^5 + 2.525 \times 10^4 = 1.655 \times 10^5 \text{ W}$$

c. The net radiation gain of the side walls:

$$\dot{Q}_{13} - \dot{Q}_{32} = 6.140 \times 10^4 - 2.525 \times 10^4 = 3.615 \times 10^4 \text{ W}$$

This heat passes through the walls to the outside by conduction; for 1 m of furnace the roof gives off 201.6 kW and the products receive 165.5 kW.

ANSWER **a.** $F_{12} = 0.6180$, $F_{13} = 0.3820$ **b.** 2.016×10^5 W; 1.655×10^5 W **c.** 3.615×10^4 W

IN THE FULL BOOK

- 14 chapters and 180 problems, all with step-by-step solutions.
- A reminder box at the start of each chapter, summarizing the relations the problems rely on.
- Basic, intermediate and advanced problems, each with a dotted area for your own work.
- One-click links from each problem to its solution and back.
- A 20-page Appendix of our own at the end of the book: properties of air, water, steam, gases, R-134a, oil and glycol solution, properties of solids, transient conduction coefficients, the blackbody radiation function and surface properties, convection, boiling and condensation correlations, heat exchanger effectiveness relations, and view factors.



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