Unit 12 · Rate of Heat Flow

ANSWER KEY · FOR TEACHERS

Full marks 32

Give the marks for the points in the marking scheme; an answer in other words that says the same is right.

1 Key words

1. conduction
2. convection
3. radiation
4. temperature gradient
5. thermal conductivity
6. black body
7. emissivity
8. Stefan's law

K · 4

Each carries 0.5 mark.

2 Label the diagram

1. steam in
2. insulation
3. copper coil
4. cold water in

K · 2

Each carries 0.5 mark.

3 Multiple choice

i. **b.** W/(m K) — K · 1

From $Q/t = kA\Delta\theta/x$, $k = (Q/t)x/(A\Delta\theta)$: W m/(m^2 K) = W/(m K). W/(m^2 K^4) is the unit of Stefan's constant.

ii. **c.** radiation — K · 1

Between the Sun and the Earth is almost empty space; only radiation needs no medium.

iii. **c.** 0.7 — A · 1

$r + a + t = 1$, so $a = 1 - 0.3 - 0 = 0.7$.

iv. **c.** 200 K/m — A · 1

Lagged, the temperature falls uniformly: $(100 - 0) \div 0.50 = 200$ K/m.

v. **b.** the land heats faster than the sea, so warm air rises over the land and cooler air from the sea flows in — U · 1

Water's high specific heat capacity keeps the sea cooler by day; air over the warmer land rises by convection, and air from over the sea moves in to take its place.

4 Short answers

a. MARKING SCHEME — U · 2

- ✓ The metal pan conducts heat quickly to the food.
- ✓ The wooden or plastic handle conducts poorly, so it stays cool to hold.

b. MARKING SCHEME — U · 2

- ✓ White cloth reflects most of the Sun's radiation (absorbs little).
- ✓ So less heat reaches the body than through dark cloth.

c. MARKING SCHEME — A · 3

- ✓ $Q/t = kA(\theta_1 - \theta_2)/x$.
- ✓ The values put in, $\Delta\theta = 15$ K.
- ✓ 450 W.

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5 Long answer

ANSWER U · 4

A thick bar of the metal, lagged with insulation, has one end heated by steam in a box. Near the other end a copper coil is wound round it, through which cold water flows at a steady rate. Two thermometers in holes P and Q, a distance x apart along the bar, read θ_1 and θ_2; two more read the water entering (θ_4) and leaving (θ_3) the coil.

When all four readings are steady (the steady state), the heat conducted through the bar each second is the heat carried away by the water. In time t a mass m of water is collected:

$kA\frac{\theta_1 - \theta_2}{x}t = ms(\theta_3 - \theta_4)$, so $k = \frac{ms(\theta_3 - \theta_4)x}{At(\theta_1 - \theta_2)}$, with A the bar's cross-section and s the water's specific heat capacity.

The bar is thick and well lagged, so the heat flow is large and measurable and none is lost from the sides.

MARKING SCHEME

- ✓ The bar heated by steam at one end, cooled by water in a coil at the other, lagged.
- ✓ θ_1, θ_2 at P and Q a distance x apart; the water's θ_3, θ_4 and mass m in time t.
- ✓ At the steady state, heat through the bar = heat gained by the water.
- ✓ $k = ms(\theta_3 - \theta_4)x / (At(\theta_1 - \theta_2))$.

6 Numerical problems

a. **ANSWER** A · 4

The same heat flows through each layer: $Q/t = A\Delta\theta \div (x_1/k_1 + x_2/k_2 + x_3/k_3)$.

For 1 m^2: x/k sum = 0.004/1.0 + 0.012/0.026 + 0.004/1.0 = 0.008 + 0.462 = 0.470 m^2 K/W.

$Q/t = 20 \div 0.470 \approx$ **43 W per m^2**.

A single pane: $1.0 \times 1 \times 20 \div 0.004 =$ **5000 W per m^2** (in this simple model, ignoring the still air that clings to each side), so the trapped layer of air does almost all the insulating.

MARKING SCHEME

- ✓ The same heat flows through each layer, so the x/k add.
- ✓ Sum of x/k = 0.470 m^2 K/W.
- ✓ About 43 W per m^2.
- ✓ Single pane 5000 W per m^2: the air layer cuts the loss greatly.

b. **ANSWER** A · 3

T = 307 K, T_0 = 293 K.

$P' = A\sigma(T^4 - T_0^4) = 1.8 \times 5.67 \times 10^{-8} \times (307^4 - 293^4) \approx$ **150 W**.

MARKING SCHEME

- ✓ Temperatures in kelvin, 307 K and 293 K.
- ✓ $P' = eA\sigma(T^4 - T_0^4)$.
- ✓ About 150 W.

7 Think

ANSWER HA · 3

On the Earth the hot gases of the flame are less dense than the air round them, so the cooler, denser air pushes them up (natural convection): the flame is drawn up long, and fresh air with oxygen flows in at the bottom. Natural convection needs gravity. On the floating station nothing is "up": the hot gases don't rise, so the flame stays round, the burnt gases stay round it, little fresh oxygen reaches it, and it goes out.

MARKING SCHEME

- ✓ On the Earth hot gases rise by natural convection, drawing fresh air in.
- ✓ Natural convection depends on gravity (buoyancy).
- ✓ In free fall there is no convection: the burnt gases stay, oxygen runs short, and the flame dies.

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8 Activity: Which cup cools fastest?

(not marked)

WHAT STUDENTS SHOULD FIND

The cup wrapped in wool cools slowest: the wool traps still air, a very poor conductor, and slows the loss of heat by conduction and convection. Between the bare steel and glass cups the difference is small, since most heat leaves from the open top (by convection and evaporation) and from the outer surface into the air, which is a poor conductor whatever the cup.

See it at Science Playground

Exhibits and plants at the center, Bhaktapur, that go with this unit. Book a class visit at science-playground.com/booking.

- **Which Feels Cooler?** (exhibit): Touch the wood, then the metal: at the same temperature the metal feels colder, because its far greater thermal conductivity draws heat from your skin faster.
- **Lava Lamp — Convection in Motion** (exhibit): Warm wax rises and cooled wax sinks in a steady loop: natural convection, heat carried upward by the moving fluid itself.
- **The Blackest Black** (exhibit): The center square is a hole into a dark box: light bounces round inside, absorbed a little each time, the way a cavity black body works.
- **The Inverse Square Law** (exhibit): Count the squares lit at one distance and at twice it: four times the area, a quarter as bright, as the Sun's power spreads over $4\pi r^2$.

Marks by level	Knowledge	Understanding	Application	Higher ability	Total
Marks	8	9	12	3	**32**