BOILING AN EGG

A TYPICAL MEDIUM SIZED EGG HAS A MASS OF 50gm AND CAN BE IDEALIZED AS A SPHERE OF WATER WITH DIAMETER OF 50 mm ...

IF IT IS TAKEN FROM THE FRIDGE AT 4°C, HOW LONG WILL IT TAKE FOR ITS INTERIOR TO REACH AN AVERAGE TEMPERATURE OF 65°C? (SAFE TO EAT, NON-RUNNY WHITE AND YOKE).

EGG: $A_s = \pi D^2 = \pi (50 \times 10^{-3})^2 = 7.854 \times 10^{-3}\ m^2$

$\text{VOLUME} = \frac{1}{6}\pi D^3 = \frac{1}{6}\pi (50 \times 10^{-3})^3 = 65.45 \times 10^{-6}\ m^3$

$\rho = 994\ kg/m^3$ (WATER AT AVG. TEMP., APPROX).

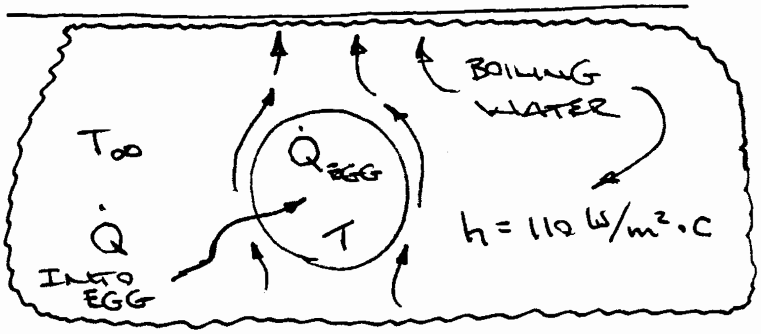
$C_p = 4178\ J/kg \cdot C$ (" " " " ")

WATER: $T = 100\ °C$ (ITS BOILING)

$\dot{Q}_{\text{INTO EGG}} = \dot{Q}_{\text{STORED IN EGG}}$

$hA_s(T_\infty - T)\, dT = mC_p\, dT$

So $\dfrac{d(T-T_\infty)}{T-T_\infty} = -\dfrac{hA}{mC_p}\, dT$



INTEGRATE THIS FROM $t = 0$ @ $T = T_i$ = INITIAL TEMP.
TO t @ $T = T(t)$, GIVES

$$\ln \frac{T(t) - T_\infty}{T_i - T_\infty} = -\frac{hA_s}{mC_p} t \qquad \text{NOW SET } b = \frac{hA_s}{mC_p}$$

$$\text{So } \ln \frac{T(t) - T_\infty}{T_i - T_\infty} = -bt \qquad \text{AND } \frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt}$$

IN OUR CASE:

$$t = \frac{\ln \frac{T(t) - T_\infty}{T_i - T_\infty}}{-b}$$

$$b = \frac{hA_s}{mC_p} = \frac{(110)(7.854\times10^{-3})}{(50\times10^{-3})(4178)} = 0.00436$$

$$= \frac{\ln\left[\frac{65-100}{4-100}\right]}{-0.00436}$$

$= 243.975$ s

$= 4.07$ MINUTES ! THE PERFECT BOILED EGG.

AMAZING THAT WORKED OUT SO WELL EH!?

BUT IS IT ACCURATE?

THIS CALCULATION METHOD ONLY APPLIES TO A 'LUMP SYSTEM'.

IS AN EGG A LUMP SYSTEM?

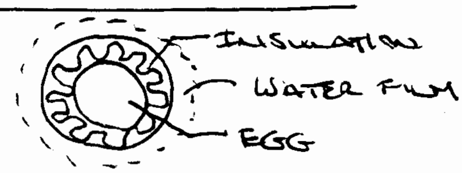
CHECK ... $Bi = \frac{L_c/k}{1/h}$ IF $Bi \le 0.1$ THEN ITS A LUMP SYSTEM.

L_c = CHARACTERISTIC LENGTH $= \frac{\text{VOLUME}}{\text{SURFACE AREA}} = \frac{65.45\times10^{-6}\ m^3}{7.854\times10^{-3}\ m^2} = 0.00833$ m

k = CONDUCTIVITY $= 0.623$ W/m.C (LIKE WATER)

SO $Bi = \frac{[0.00833/0.623]}{[1/110]} = 1.47 > 0.1$ $\therefore$ MY CALCS ARE TOAST!

NOTE: IF THE EGG WERE INSULATED



$Bi = \frac{L_c/k}{R}$; R = THERMAL RESISTANCE OF OUTSIDE.

IF YOU INSULATED THE EGG $Bi \le 0.1$ IS POSSIBLE.

NOTE ALSO: $b = \frac{A_s}{mC_pR}$ (SEE TOP OF THIS PAGE)

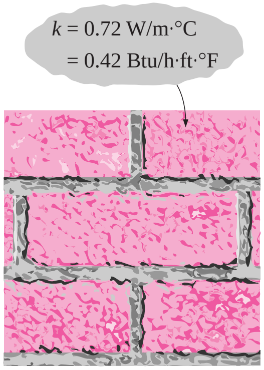


FIGURE 16–10
The thermal conductivity value in English units is obtained by multiplying the value in SI units by 0.5778.

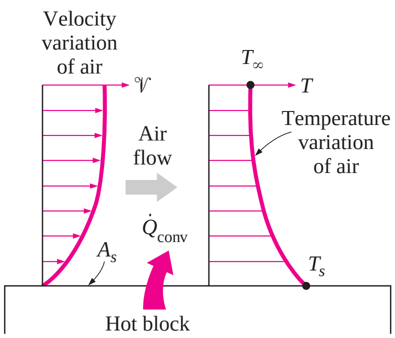


FIGURE 16–11
Heat transfer from a hot surface to air by convection.

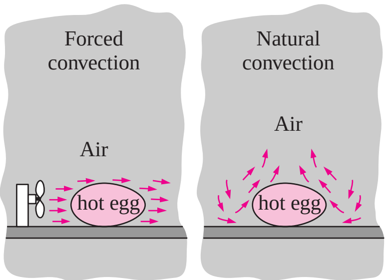


FIGURE 16–12
The cooling of a boiled egg by forced and natural convection.

Discussion Note that the thermal conductivity value of a material in English units is about half that in SI units (Fig. 16–10). Also note that we rounded the result to two significant digits (the same number in the original value) since expressing the result in more significant digits (such as 0.4160 instead of 0.42) would falsely imply a more accurate value than the original one.

16–3 ▪ CONVECTION

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion.* The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Consider the cooling of a hot block by blowing cool air over its top surface (Fig. 16–11). Energy is first transferred to the air layer adjacent to the block by conduction. This energy is then carried away from the surface by convection, that is, by the combined effects of conduction within the air that is due to random motion of air molecules and the bulk or macroscopic motion of the air that removes the heated air near the surface and replaces it by the cooler air.

Convection is called **forced convection** if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called **natural** (or **free**) **convection** if the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid (Fig. 16–12). For example, in the absence of a fan, heat transfer from the surface of the hot block in Fig. 16–11 will be by natural convection since any motion in the air in this case will be due to the rise of the warmer (and thus lighter) air near the surface and the fall of the cooler (and thus heavier) air to fill its place. Heat transfer between the block and the surrounding air will be by conduction if the temperature difference between the air and the block is not large enough to overcome the resistance of air to movement and thus to initiate natural convection currents.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Despite the complexity of convection, the rate of *convection heat transfer* is observed to be proportional to the temperature difference, and is conveniently expressed by **Newton's law of cooling** as

$$\dot{Q}_{conv} = hA_s\,(T_s - T_\infty) \qquad \text{(W)} \tag{16–4}$$

where h is the *convection heat transfer coefficient* in W/m^2 · °C or Btu/h · ft^2 · °F, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

The convection heat transfer coefficient h is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Typical values of h are given in Table 16–5.

Some people do not consider convection to be a fundamental mechanism of heat transfer since it is essentially heat conduction in the presence of fluid motion. But we still need to give this combined phenomenon a name, unless we are willing to keep referring to it as "conduction with fluid motion." Thus, it is practical to recognize convection as a separate heat transfer mechanism despite the valid arguments to the contrary.

TABLE 16–5

Typical values of convection heat transfer coefficient

Type of convection	h, W/m$^2 \cdot$ °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

*Multiply by 0.176 to convert to Btu/h · ft^2 · °F.

EXAMPLE 16–4 Measuring Convection Heat Transfer Coefficient

A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C, as shown in Fig. 16–13. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°C in steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

SOLUTION The convection heat transfer coefficient for heat transfer from an electrically heated wire to air is to be determined by measuring temperatures when steady operating conditions are reached and the electric power consumed.

Assumptions **1** Steady operating conditions exist since the temperature readings do not change with time. **2** Radiation heat transfer is negligible.

Analysis When steady operating conditions are reached, the rate of heat loss from the wire will equal the rate of heat generation in the wire as a result of resistance heating. That is,

$$\dot{Q} = \dot{E}_{\text{generated}} = VI = (60\text{ V})(1.5\text{ A}) = 90\text{ W}$$

The surface area of the wire is

$$A_s = \pi DL = \pi(0.003\text{ m})(2\text{ m}) = 0.01885\text{ m}^2$$

Newton's law of cooling for convection heat transfer is expressed as

$$\dot{Q}_{\text{conv}} = hA_s\,(T_s - T_\infty)$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{conv}}}{A_s(T_s - T_\infty)} = \frac{90\text{ W}}{(0.01885\text{ m}^2)(152 - 15)°\text{C}} = \mathbf{34.9\ W/m^2 \cdot °C}$$

Discussion Note that the simple setup described above can be used to determine the average heat transfer coefficients from a variety of surfaces in air. Also, heat transfer by radiation can be eliminated by keeping the surrounding surfaces at the temperature of the wire.

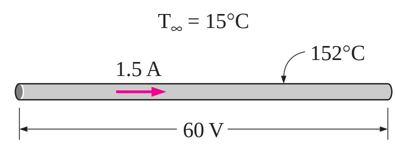


FIGURE 16–13
Schematic for Example 16–4.