280.371 Process Engineering Operations

Drying Problems Tutorial 2

Example 2

Lecture 4

Example 2: Evaporation from a wet surface (convection and radiation heat transfer)
A 10cm by 20cm steak is placed under a grilling element to cook. The wet bulb and dry bulb temperatures of the air above the steak are $43^{o}C$ and $100^{o}C$, respectively, and the element temperature is $500^{o}C$. The radiation view factor may be taken to be 1 and conduction from under the steak may be ignored. Saturation humidities at $60^{o}C$, $70^{o}C$, $80^{o}C$ and 90^{o} are 0.15, 0.28, 0.55 and 1.4 kg/kg, respectively.

(a) Calculate the initial rate of evaporation from the surface of the steak assuming the surface is wet and the heat transfer coefficient to the steak is 8 $W/m^2\ K$. . What will the surface temperature of the steak be?

(b) How long will it take to reduce the moisture content of the steak from 2.0 to 1.5, assuming that the steak is 5mm thick with a dry density of 600 kg/m^3 ?

C_p moist air 1071 J /kg K

$$h_{rad} = F_{12}\ 5.67\times10^{-8}(T_{rad}+T_s)(T_{rad}^2+T_s^2) \quad W/m^2\ K$$

Temperatures in Kelvins.

Generic Solution Procedure

1 Calculate the mass transfer coefficient from the Lewis analogy

2 Assume a surface temperature

3 Determine the surface saturation humidity from the psychrometric chart

4 Calculate the rate of evaporation using the mass transfer equation

5 Calculate the rate of evaporation using the heat transfer equation

6 If the rates from steps 4 and 5 are the same, you guessed correctly. Otherwise go back to step 2

Heat & mass transfer equations

- The rate of mass transfer = drying rate

$$m_v = k_H^{'} A(H_{surface} - H_{air})$$

$$R = k_H^{'}(H_{surface} - H_{air})$$

- The rate of heat transfer to provide drying rate, m_v

$$\phi = m_v h_{fg}$$

$$R = \frac{\phi}{h_{fg} A}$$

- h_{fg} is the latent heat of evaporation evaluated at the surface temperature
- $\phi = q$

= rate of heat transfer (W)

$$R = \frac{kg\ water}{m^2 s}$$

Slide 10 in Course Notes

Heat & Mass transfer analogy

- The mass transfer coefficient analogy with the heat transfer coefficient is:

$$k_H^{'} \approx \frac{h}{c_{pH}}$$ Lewis relationship

$$c_{pH} = c_{p,air} + H_{air}\, c_{p,steam}$$

$C_{p,air}$ – specific heat of dry air at θ_{air}

$C_{p,steam}$ – specific heat at θ_{WB}

Slide11 in Course Notes

Convection & radiation

- *Convection and radiation from above*

$$\phi = h_c A(\theta_{air} - \theta_{surface}) + h_{rad} A(\theta_{radr} - \theta_{surface})$$

Slide 17 in Course Notes

$$h_{rad} = F_{12}\ 5.67 \times 10^{-8} (T_{rad} + T_s)(T_{rad}^2 + T_s^2) \quad W/m^2 K$$

Temperatures in Kelvins.

h_{rad} "pseudo heat transfer coefficient" for radiation

F_{12} View factor [-] (assume a value of 1)

5.67×10^{-8} w m^{-2} K^{-4} this is the value of the Stefan-Boltzmann constant, σ .

T_{rad} Temperature of radiating heat source, K.

$T_{surface}$ Temperature of surface, K.

θ_{rad} Temperature of radiating heat source, ^oC.

$\theta_{surface}$ Temperature of surface, ^oC.

$\theta = 100^{o} C$

$\theta_{wb} = 43^{o} C$

$\Rightarrow H_{air} = 0.0325\ kg/kg$

$\Rightarrow c_p = c_{pair} + H_{air} c_{psteam}$

= 1006+ 0.0325 x 2000

= 1071

Iteration step 1

(1)

Example 2.

Air temperature 100°C (dry bulb); wet bulb temp 43°C.
Element temperature 500°C.
Radiation view factor 1 (F_{12})
Conduction under steak can be ignored.

Saturation Humidities GIVEN

60°C	70°C	80°C	90°C	
0.15	0.28	0.55	1.4	kg/kg

$h = 8\ W/m^2K$ find K'_H using Lewis relationship SLIDE 11 *

$K'_H = \frac{8}{1071} = 7.47 \times 10^{-3}\ kg/m^2s$

- Guess steak surface temperature 60°C $H_s = 0.15$ (given)

- Mass transfer SLIDE 10 *

Hair from chart = 0.033 kg/kg

(.0325)

$R_c = 7.47 \times 10^{-3}(0.15 - 0.033) = 8.7 \times 10^{-4}\ kg/m^2s$

- Heat transfer SLIDE 17 *

$R = [h(\theta_{air} - \theta_s) + h_{rad}(\theta_{element} - \theta_s)] / h_{fg}$

$= \frac{8(100-60) + 5.67 \times 10^{-8}(773+333)(773^2+333^2)(500-60)}{2358000}$

h_{fg} at 60°C

$= 8.43 \times 10^{-3}\ kg/m^2s$

10 times as much as mass transfer eq. predicts.

Iteration step 2

Example 2 contd.

(2)

Re do calculation with another surface temp.

Assume $88^\circ C = 361\ K$

- Mass transfer

$$R = 7.47\times10^{-3}\,(1.11 - 0.033) = \underline{\underline{8.045\times10^{-3}\ kg/m^2 s}}$$

- Heat transfer

$$R = \frac{8(100-88) + 5.67\times10^{-8}(773+361)(773^2+361^2)\times(500-88)}{2{,}288{,}000}$$

$$= 8.47\times10^{-3}\ kg/m^2 s$$

Close to mass transfer answer
so use this as the answer

(b) Time to reduce moisture

$$t = \frac{s\,\rho_s}{R}\,(X_1 - X_2)$$

$$= \frac{5\times10^{-3}\times600}{8.47\times10^{-3}}\,(2-1.5)$$

$$= 177\ s \qquad (\sim 3\ \text{minutes}).$$