MTRL 361: Modelling of Materials Processes | 2019

Mini Project 2: Due date: Friday, November 29th, 2019

Point Grey Lime operates a 3.60 m OD x 100 m rotary lime kiln. As plant engineer you have been asked to develop a 1-D steady-state model to calculate the axial temperature profiles (gas, solids and refractory hot-face) and percent conversion starting at the charge-end and extending over the first 90 m of the kiln. A summary of operating data is attached. Being in sunny and warm Point Grey, the feed limestone (100% $CaCO_3$) is bone-dry.

It is known that calcination starts at 820°C:

$$CaCO_3 \Rightarrow CaO + CO_2 \qquad \mathrm{Q_{reaction}} = 1790 \quad \text{kJ per } \mathrm{kg_{CaCO_3}} \quad \text{(endothermic)}$$

Above this temperature you can assume that 85% of the total heat transfer rate to the bed goes to drive this reaction and the remainder is absorbed as sensible heat to increase the bed temperature.

Create a V-B code to calculate the temperatures of the bed, gas and hot face, solid and gas mass flow as well as percent conversion over the first 90 m (use the size step of 1 m). In setting-up the model, the V-B module should:

- Begin with a subroutine ***'MainEuler'*** to interact with the worksheet and control model operations. Within ***'MainEuler'*** you should call individual subroutines as required, e.g. '***Euler'*** subroutine to use Euler method to calculate the gas and bed temperatures and the mass flow of CaCO3.
- Within the Euler subroutine, ***'RefractoryHeatBalance'*** subroutine should be called to calculate $\overline{\mathbf{T}}_{\mathbf{hf}}$, and ***'Massflow'*** subroutine to calculate the gas and solid bed mass flow considering the calcination reaction.
- The ***'RefractoryHeatBalance'*** subroutine uses bisection method to find $\overline{\mathbf{T}}_{\mathbf{hf}}$ for the current values of $\mathbf{T_g}$ and $\mathbf{T_b}$. Within this subroutine call ***'HeatTransferRates'*** subroutine to calculate $\dot{\mathbf{Q}}_{\mathbf{b}}, \dot{\mathbf{Q}}_{\mathbf{g}}, \dot{\mathbf{Q}}_{\mathbf{ew \to eb}}, \dot{\mathbf{Q}}_{\mathbf{cw \to cb}}, \dot{\mathbf{Q}}_{\mathbf{shell}}$.
- Code, debug and understand the Euler method before attempting the next step (RK method).

- Repeat the above steps to write a V-B code using **Runge-Kutta** method instead of Euler ('***MainRK'*** subroutine)**.** The ***'RefractoryHeatBalance', 'HeatTransferRates', and 'Massflow'*** subroutines are common between ***'MainEuler'*** and ***'MainRK'.***

This is a complex model; using the suggested structure will greatly reduce the time required for debugging. Getting the Runge-Kutta method operating correctly may be time-consuming; concentrate on the Euler method first.

All numerical calculations such as ODE solutions should be performed in V-B. Basic calculations such as unit conversion and refractory resistance calculation can be done in the spreadsheet (as shown in model setup sheet).

Submit a written report covering the following items:

1. For the Euler method plot bed, gas and hot face temperatures and percent conversion over the first 90 m. Use a step size of 1m; put all plots on a single chart; primary y-axis is temperature; secondary y-axis is % conversion.

2. For the RK method plot bed and freeboard gas mass flows over the first 90 m and comment on the results; i.e. why does $\dot{m}_b$ decrease and $\dot{m}_g$ increase after calcination begins?

3. For both the Euler and RK methods run the model using step size of 1m. Summarize the results in tabular form comparing bed temperature, gas temperature and % conversion at 90m.

4. Based on the operating data (measured T_b and % conversion at 90 m) discuss the accuracy of the two methods for a given step size

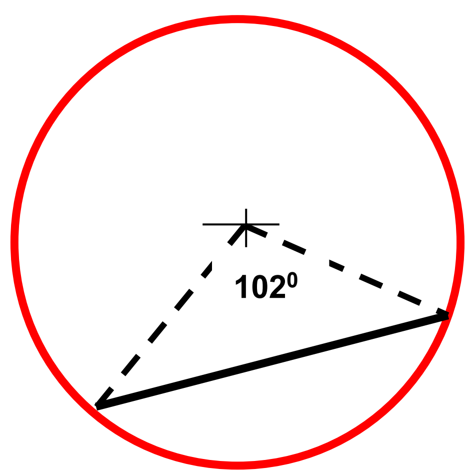
5. For the Euler Method (1 m step size) plot the radiative heat-transfer coefficients for the gas-to-exposed-wall and gas-to-exposed-bed. Based on this plot discuss the relative importance of radiation and convection on heat transfer to the exposed-wall and exposed bed surfaces at 5 m and 90 m into the kiln.

NOTE

ALL TEMPERATURES TO BE REPORTED IN CELCIUS NOT KELVIN

<u>**OPERATING AND DESIGN DATA**</u>

Production rate	450 tonnes CaO per day
Fill (see attached figure)	12%
Solids charge temperature	25ºC
Off-gas temperature	580ºC
Ambient temperature	25ºC
Off-gas mass flow	2.85 times charge feed rate
Bed temperature @ 90 m (measured)	1170ºC
Conversion @ 90 m (measured)	78%
Refractory thickness	8"
Refractory thermal conductivity	3.0 W/m ºC



Bed Geometry at 12% fill

Heat Transfer Equations

Refractory/Shell Thermal Resistance:

$$R = \frac{1}{h_{shell}\pi\left(D_{os}\right)} + \frac{\ln\left(D_{os}/D_{is}\right)}{2\pi\, k_{ref}} \qquad (\mathrm{m^oC/W})$$

where: D_{os} is the outside diameter
D_{is} is the inside diameter

Convection Heat-transfer coefficients (W/m^{2o}C):

$h_{C,g\text{-}ew}=30$ $h_{C,g\text{-}eb}=110$ $h_{cw\text{-}cb}=125$ $h_{shell}=20$

Radiative Heat Transfer Coefficients (W/m^{2}K^o):

Exposed Wall to Exposed Bed:

$$h_{R,ew\rightarrow eb} = \frac{5.67x10^{-8}\left(1-\varepsilon_g\right)\left(\overline{T}_{hf}^4 - T_b^4\right)L_{ew}}{\left[\dfrac{1}{\varepsilon_{eb}} + \dfrac{L_{eb}}{L_{ew}}\left(\dfrac{1}{\varepsilon_{ew}} - 1\right)\right]\mathrm{L_{ew}}\left(\overline{\mathrm{T}}_{\mathrm{hf}} - T_b\right)}$$

Gas to Exposed Wall: $$h_{R,g\rightarrow ew} = \frac{5.67x10^{-8}\,\varepsilon_g\,(T_g^4 - \overline{T}_{hf}^4)}{T_g - \overline{T}_{hf}}$$

Gas to Exposed Bed: $$h_{R,g\rightarrow eb} = \frac{5.67x10^{-8}\,\varepsilon_g\,(T_g^4 - T_b^4)}{T_g - T_b}$$

where : $\varepsilon_g=0.3$ (gas radiative emissivity and absorptivity)
$\varepsilon_g=0.9$ (radiative emissivity of the exposed bed)
$\varepsilon_g=0.8$ (radiative emissivity of the exposed wall)

L_{eb} = Exposed bed chord length (m)

L_{ew} = Exposed wall arc length (m)

L_{cw} = Exposed wall arc length (m)

All Temperatures for Radiative Calculations are in Kelvin

Specific Heats:	Gas:	1050 J/kg^{o}C	Bed:	850 J/kg^{o}C
Molecular Weights:	$CaCO_3$;	100.1		CaO ; 56.1