Control Element (Group 16)

In this fast pyrolysis system, we have chosen an electrical heater to produce heat to the pyrolysis reactor which is the rotating cone. Besides, we have included a temperature controller in order to maintain the desired temperature.

The transfer function of the temperature controller is shown below:

Unsteady-state energy balance for the reactor and heating element:

{Energy in} – {Energy out} + {Heat generated} = {Energy Accumulated}

Reactor: $wC\left(T_i - T_{ref}\right) - wC\left(T - T_{ref}\right) + h_e A_e (T_e - T) = \frac{mC(dT - T_{ref})}{dt}$ ------------ > (1)

$wC(T_i - T) + h_e A_e (T_e - T) = \frac{mCdT}{dt}$ -- > (2)

Heating element: $Q - h_e A_e (T_e - T) = \frac{m_e C_e dT_e}{dt}$ --- > (3)

Steady-state energy balance for reactor and heating element:

Reactor: $wC(\overline{T_i} - \overline{T}) + h_e A_e (\overline{T_e} - \overline{T}) = 0$ -- > (4)

Heating element: $\bar{Q} - h_e A_e (\overline{T_e} - \overline{T}) = 0$ -- > (5)

Subtracting equation 4 from equation 2 and equation 5 from equation 3:

Reactor: $wC[(T_i - \overline{T_i}) - (T - \overline{T})] + h_e A_e [(T_e - \overline{T}_e) - (T - \overline{T}) = \frac{mCd(T - \overline{T})}{dt}$ ---------- > (6)

Heating element: $(Q - \bar{Q}) - h_e A_e [(T_e - \overline{T}_e) - (T - \overline{T})] = \frac{m_e C_e d(T_e - \overline{T_e})}{dt}$ --------------- > (7)

Deviation equation for reactor and heating elements:

Reactor: $wC(T_i{}' - T') + h_e A_e (T_e{}' - T') = \frac{mCdT'}{dt}$ -- > (8)

Heating element: $Q' - h_e A_e (T_e{}' - T') = \frac{m_e C_e dT_e{}'}{dt}$ --- > (9)

Note that $\frac{dT}{dt} = \frac{dT'}{dt}$ ***and*** $\frac{dT_e}{dt} = \frac{dT_e{}'}{dt}$***. Multiply equation 8 by*** $\frac{1}{wC}$ ***and equation 9 by*** $\frac{1}{h_e A_e}$ ***:***

Reactor: $-(T' - T_i{}') + \frac{h_e A_e}{wC}(T_e{}' - T') = \frac{m}{w}\frac{dT'}{dt}$ --- > (10)

Heating elements: $\frac{Q'}{h_e A_e} - (T_e{}' - T') = \frac{m_e C_e}{h_e A_e}\frac{dT_e{}'}{dt}$ -- > (11)

Applying Laplace Transform for both equation 10 and 11:

Reactor: $T_i'(s) - T'(s) + \frac{h_eA_e}{wC}T_e'(s) - \frac{h_eA_e}{wC}T'(s) = \frac{m}{w}[sT'(s) - T'(0)]$ ------------ > (12)

At initial steady-state, $\boldsymbol{T'(0) = 0}$,

$$T_i'(s) - T'(s) + \frac{h_eA_e}{wC}T_e'(s) - \frac{h_eA_e}{wC}T'(s) = \frac{m}{w}sT'(s) \text{ --------------- > (13)}$$

$$T'(s)\left[\frac{m}{w}s + 1 + \frac{h_eA_e}{wC}\right] = T_i'(s) + \frac{h_eA_e}{wC}T_e'(s) \text{ ------------------------ > (14)}$$

Heating element: $\frac{Q'(s)}{h_eA_e} - (T_e'(s) - T'(s)) = \frac{m_eC_e}{h_eA_e}[sT_e'(s) - T_e'(0)]$ ---------------- > (15)

At initial steady-state, $\boldsymbol{T_e'(0) = 0}$,

$$\frac{Q'(s)}{h_eA_e} - T_e'(s) + T'(s) = \frac{m_eC_e}{h_eA_e}sT_e'(s) \text{ ---------------------------------- > (16)}$$

$$T_e'(s)\left[\frac{m_eC_e}{h_eA_e}s + 1\right] = T'(s) + \frac{Q'(s)}{h_eA_e} \text{ -------------------------------------- > (17)}$$

Since $\boldsymbol{T_e'(s)}$ is an intermediate element, we rearrange both equations 14 and 17 and eliminate $\boldsymbol{T_e'(s)}$.

$$\left[\frac{mm_eC_e}{wh_eA_e}s^2 + \left(\frac{m_eC_e}{h_eA_e} + \frac{m_eC_e}{wC} + \frac{m}{w}\right)s + 1\right]T'(s) = \left(\frac{m_eC_e}{h_eA_e}s + 1\right)T_i'(s) + \frac{1}{wC}Q'(s) \text{ -------- > (18)}$$

Due to the influence of both inputs on the dynamic behavior of $\boldsymbol{T'}$, it is necessary to develop two transfer functions for the model. The effect of Q' on T' can be derived by assuming $\boldsymbol{T_i}$ is constant at its nominal steady-state value, $\boldsymbol{\bar{T}_i}$. Thus, $\boldsymbol{T_i' = 0}$ and equation 18 can be rearranged as:

$$\frac{T'(s)}{Q'(s)} = \frac{\frac{1}{wC}}{b_2s^2 + b_1s + 1} = G_1(s) \text{ ------------------ > (19)} \qquad (T_i'(s) = 0)$$

$$\frac{T'(s)}{T_i'(s)} = \frac{\frac{m_eC_e}{h_eA_e}s + 1}{b_2s^2 + b_1s + 1} = G_2(s) \text{ ------------------ > (20)} \qquad (Q'(s) = 0)$$

Where,

$$b_1 = \frac{m_eC_e}{h_eA_e} + \frac{m_eC_e}{wC} + \frac{m}{w} \text{ --------- > (21)}$$

$$b_2 = \frac{mm_eC_e}{wh_eA_e} \text{ ----------------------- > (22)}$$

By using Superposition Principle, the effect of simultaneous changes in both inputs, $\boldsymbol{Q'(s)}$ and $\boldsymbol{T_i'(s)}$ is given by:

$$T'(s) = G_1(s)Q'(s) + G_2(s)T_i'(s) \text{ --------- > (23)}$$

The order of the transfer function is first order.

Controlled variables: - Temperature of reactor (K)

- Pressure of reactor (Pa)

Manipulated variables: - Input from dryer (kg/hr)

Disturbance variables: - Feedstock (biomass) (kg/hr)

In our reactor design, we choose to use PID controller in our reaction. We choose PID over P and PI controllers because by using P controller alone, the offset that occurs after a set-point change or a sustained disturbance will not be eliminated and causes imperfection to the system. Besides, using PI controller will produce oscillatory response to the system and causes reset windup. When a sustained error occurs, the integral term in the integral controller will become large and the controller output will eventually saturates and leads to reset windup. Therefore, a derivative integral is much recommended to be added in the system as it anticipates the future error by considering its rate of change. With the presence of PID controllers, the oscillations created can be reduced and there will be no offset which benefits the system.

PID controller algorithm is:

$$p(t) = \bar{p} + K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t')dt' + \tau_D \frac{de}{dt} \right]$$

The transfer function for PID controller is:

$$\frac{\mathrm{P}'(\mathrm{s})}{\mathrm{E}(\mathrm{s})} = K_c \left(1 + \frac{1}{\tau_I s} + \tau_D s \right)$$