BACKGROUND:

A mathematical model implemented in Simulink for battery cooling system (BCS) as well as closed loop feedback controller is provided. The closed loop system monitors the battery temperature and compares with SET POINT value. Based on offset, a coolant flow rate correction is added to the supplied coolant to BCS. System eventually becomes self-controlled and achieves battery temperature closer to SET POINT VALUE.

For reference, a PID controller with default settings attached to BCS system to form closed loop is provided as Simulink model. Battery heat generation rate (J/sec) is given as input in BCS model. Same needs to be used for all simulations work. It is advised to observe the BCS model based on set of mathematical equations added in appendix in this document. Candidate has to use the same model without any change.

PROBLEM STATEMENT:

Objective is to arrive at best set of values of battery cooling system controller PID gains (Kp, Ki , Kd) that helps in achieving targeted battery outlet temperature

1. **in least amount of time,**
2. **with near zero OFFSET and**
3. **with minimal over/under shoots in battery temperature**

Limitations on PID gains (Kp, Ki , Kd) due to issues in practical implementation are as follows:

0.1 < Kp < 10

0.1 < Ki < 10

0.1 < Kd < 10

TASKS TO BE PERFORMED:

Candidate is expected to run battery cooling system WITHOUT controller as shown in figure 1.0 and plot:

- ✓ **Battery temperature vs. time for duration of charging time (3 Hours ~ 10^4 Seconds)**
- ✓ **Observe (in plots) that battery temperature increases continuously in absence of control system.**

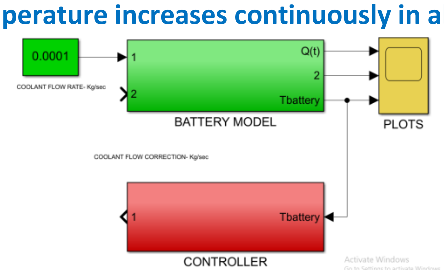

Figure 1.0

Now ADD controller by closing the loop as shown below in figure 2.0 below and re run simulations and plot:

- ✓ **Battery temperature vs. time for duration of charging time (3 Hours) using default PID settings [0 1 1] [kp ki kd]**
- ✓ **Observe some oscillations in battery outlet temperature in initial period and its final steady state value = 26 ^{0}C**
- ✓ **Observe corrected coolant flow rate vs. time for duration of charging time (3 hours)**
- ✓ **Change PID setting to following values: [1 1 0], [1 0 0] and re run simulations**

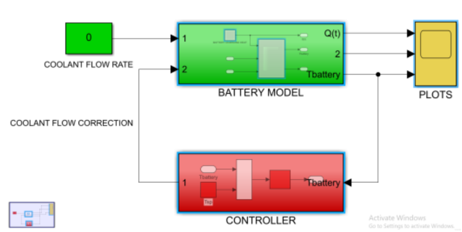

Figure 2.0

Can change scale for better readability as shown in figure 3 below:

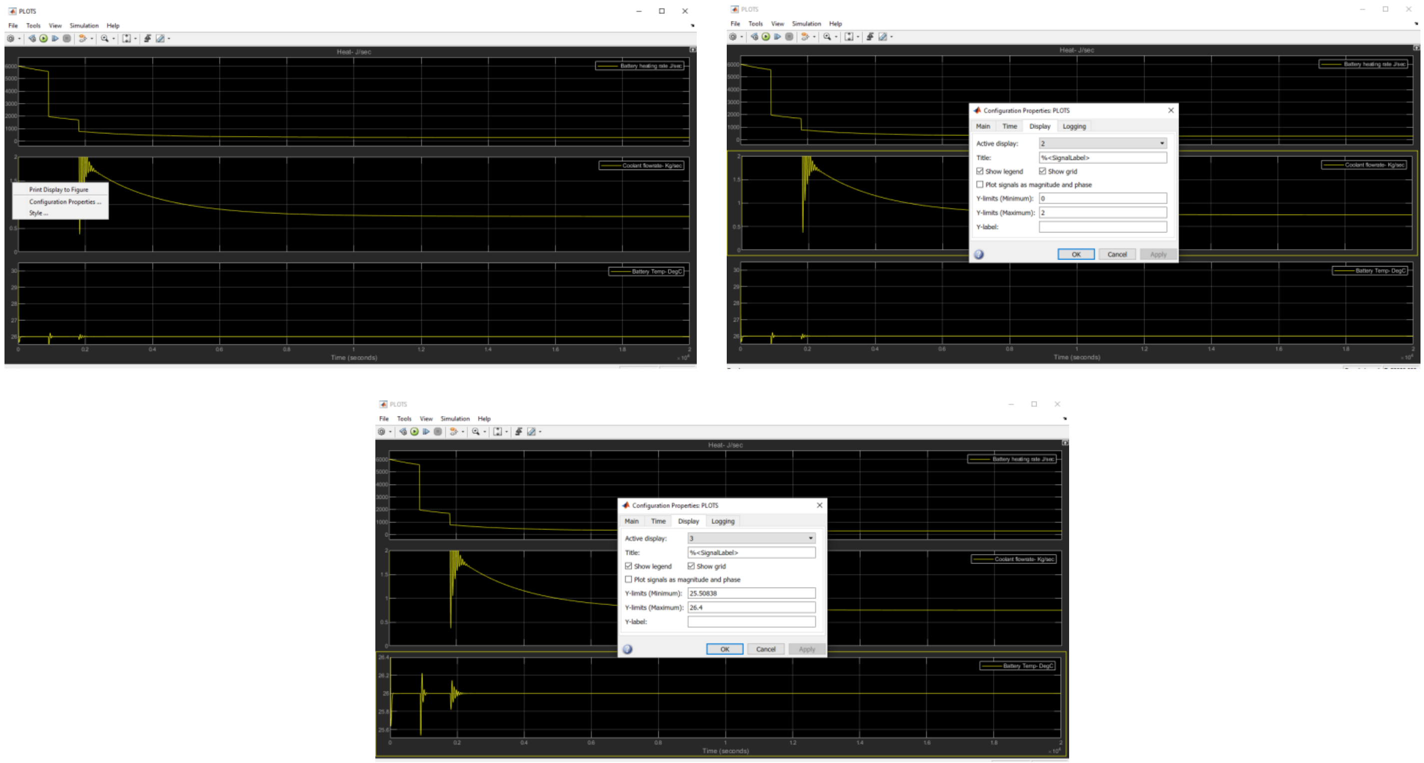

Figure 3.0

- ✓ Observe that steady state value never reaches SETPOINT (26^0 C) for [1 0 0] even though battery temperatures move smoothly without overshoots/undershoots.
- ✓ Arrive at PID settings as shown in figure 3.0 to
  a. Achieve steady state battery temperature value closest to SETPOINT Value and
  b. Achieve stability faster without oscillations etc.

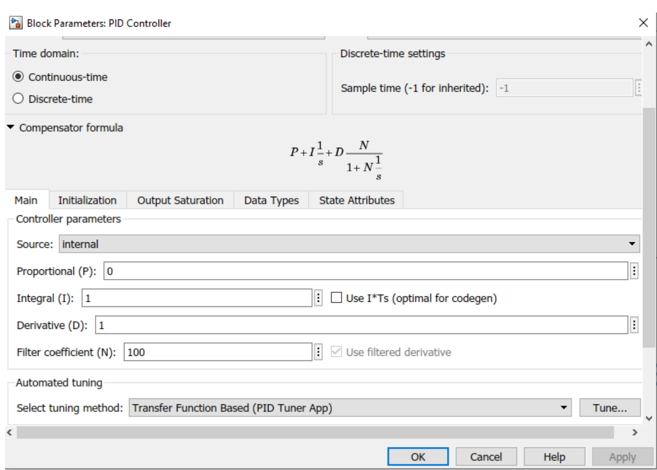

Figure 3.0

- ✓ Change SETPOINT to any other value (>26 degrees) and plot results for battery temperature and coolant flow rate for 3 hours duration.
- ✓ Arrive at best values of PID gains to achieve steady sate value of temperature closest to SETPOINT and without oscillations. Plot results for each set

Caution: don't use SET POINT value ≤ 25 as it's impossible to cool below 25 using coolant at 25!

APPENDIX

Mathematical modeling of BCS

1. Battery thermal energy balance:

$$\frac{d(M_{battery}\, C_{battery}\, T_{battery})}{dt} = Q(t) - hA(T_{battery} - T_{Coolant})$$

Correlation for heat transfer coefficient between coolant and heated battery

$h = 0.023Re^{\frac{2}{3}}Pr^{\frac{1}{3}};\ Pr = 0.7\ (for\ coolant);$

$h = heat\ transfer\ coefficient$

$\dot{Q}_{coolant} = VA_{cross\ sectional};\ \dot{m}_{coolant} = \rho\dot{Q}_{coolant}\ (Coolant\ mass\ flowrate);\ Re = \dfrac{\rho V D_h}{\mu}$

$\dot{Q}_{coolant} = Coolant\ volumetric\ flowrate;\ V = coolant\ flow\ velocity\ in\ battery\ inlet\ pipe;$

$A_{cross\ sectional} = Battery\ coolant\ inlet\ pipe\ area;$

$\dot{m}_{coolant} = Coolant\ mass\ flowrate$

The coolant mass flow-rate is proportional to flow velocity and hence "h" (heat transfer coefficient)

$Q(t) = heat\ generation\ rate\ in\ battery;\ A = Interfacial\ area\ within\ battery\ for\ heat\ trfr$

$M_{battery} = Mass\ of\ battery\ pack;\quad C_{battery} = Heat\ capacity\ of\ battery;$

$T_{battery} = Instantaneous\ temperature\ of\ battery\ pack\ (assumed\ uniform)$

$T_{Coolant} = Coolant\ temperature;$

$\rho = coolant\ density;\ \mu = coolant\ kinematic\ viscosity;\ D_h = Diameter\ of\ battery\ inlet\ pipe$

2. Coolant thermal energy balance:

$T_{Coolant} = 25^0C$

(Assumption: External chiller ensures a constant temperature coolant supply to battery pack. Heat capacity of coolant being high, its temperature nearly constant during flow within battery pack)

Mathematical modeling of PID feedback Controller

1. Battery temperature set point (desired value)

$T_{Set\ Point} = 27^0C$

2 Feedback control based on difference between ACTUAL and SET POINT value:

$$\dot{Q}_{coolant\ correction} = K_P \in + \int K_I \in dt + K_D \frac{d\in}{dt}$$

$$\in = T_{Battery} - T_{Set\ Point}$$

K_P , K_I K_D are constants to be tuned for timely and good control without oscillations, etc.

Simulink Model (ONLY FOR ILLUSTRATION PURPOSE)

- **ONLY RED COLOURED BLOCK PARAMETERS TO BE CHANGED : SET POINT, COOLANT FLOW- REFRENCE VALUE and PID PARAMETERS**