Temperature Controller Design of a Heat Exchanger within a High Temperature Oxygen Production System using a Lumped Thermal Modeling approach

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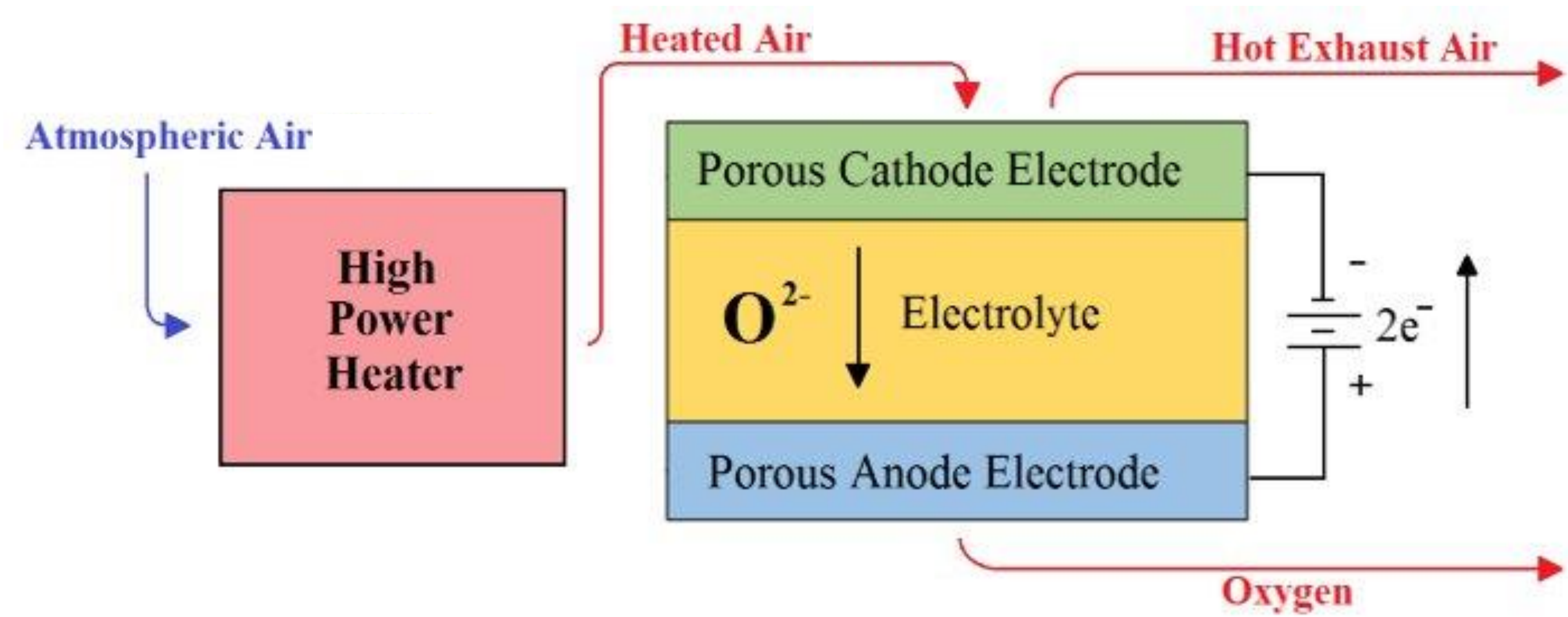
General Overview

Motivation
- Problem Statement
- Project Objective

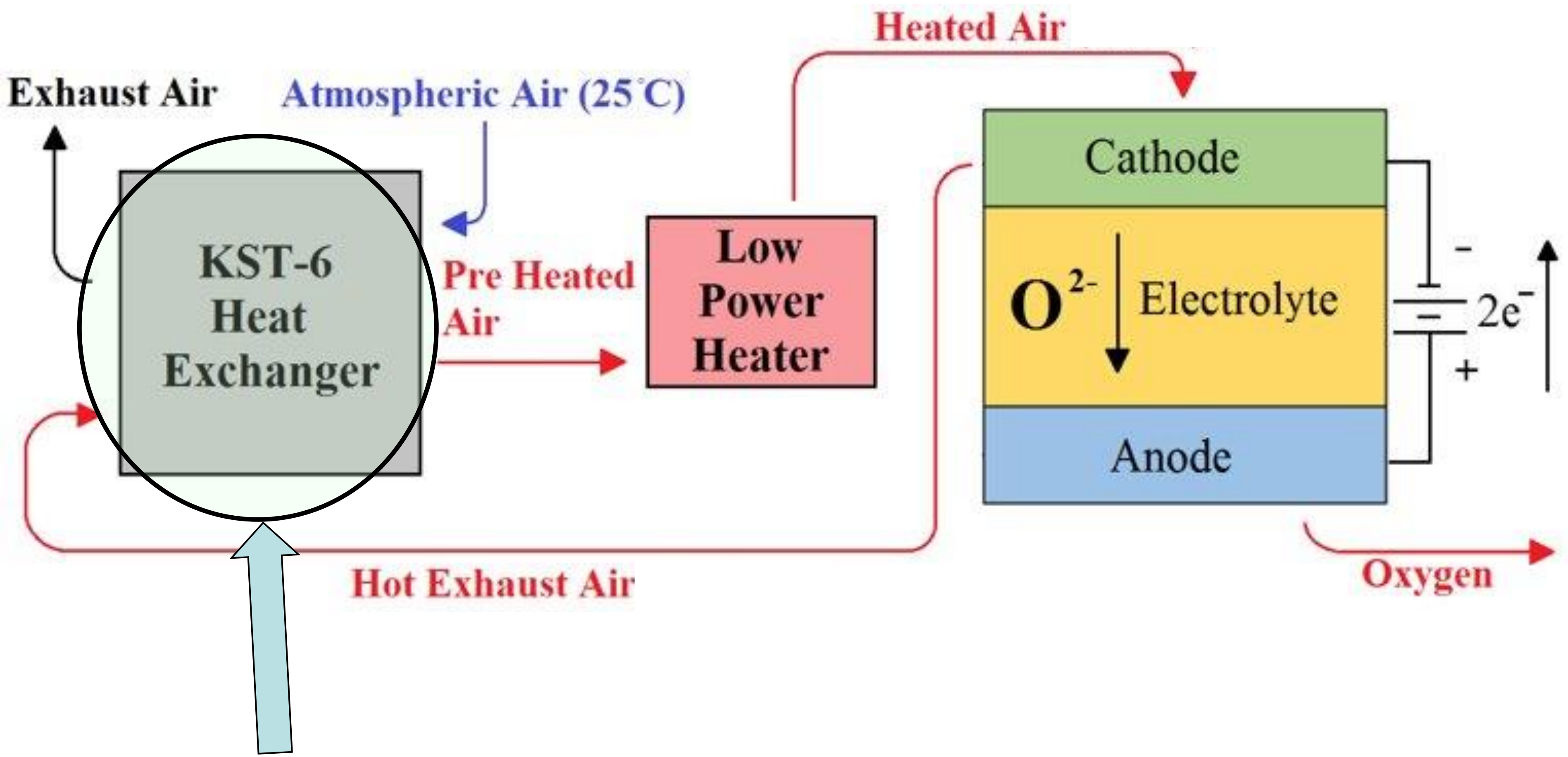
Dynamic Modeling
- Mass Balance
- Energy Balance

Controls
- State Space
- PID Tuning

O2 Production System with Pre-Heater

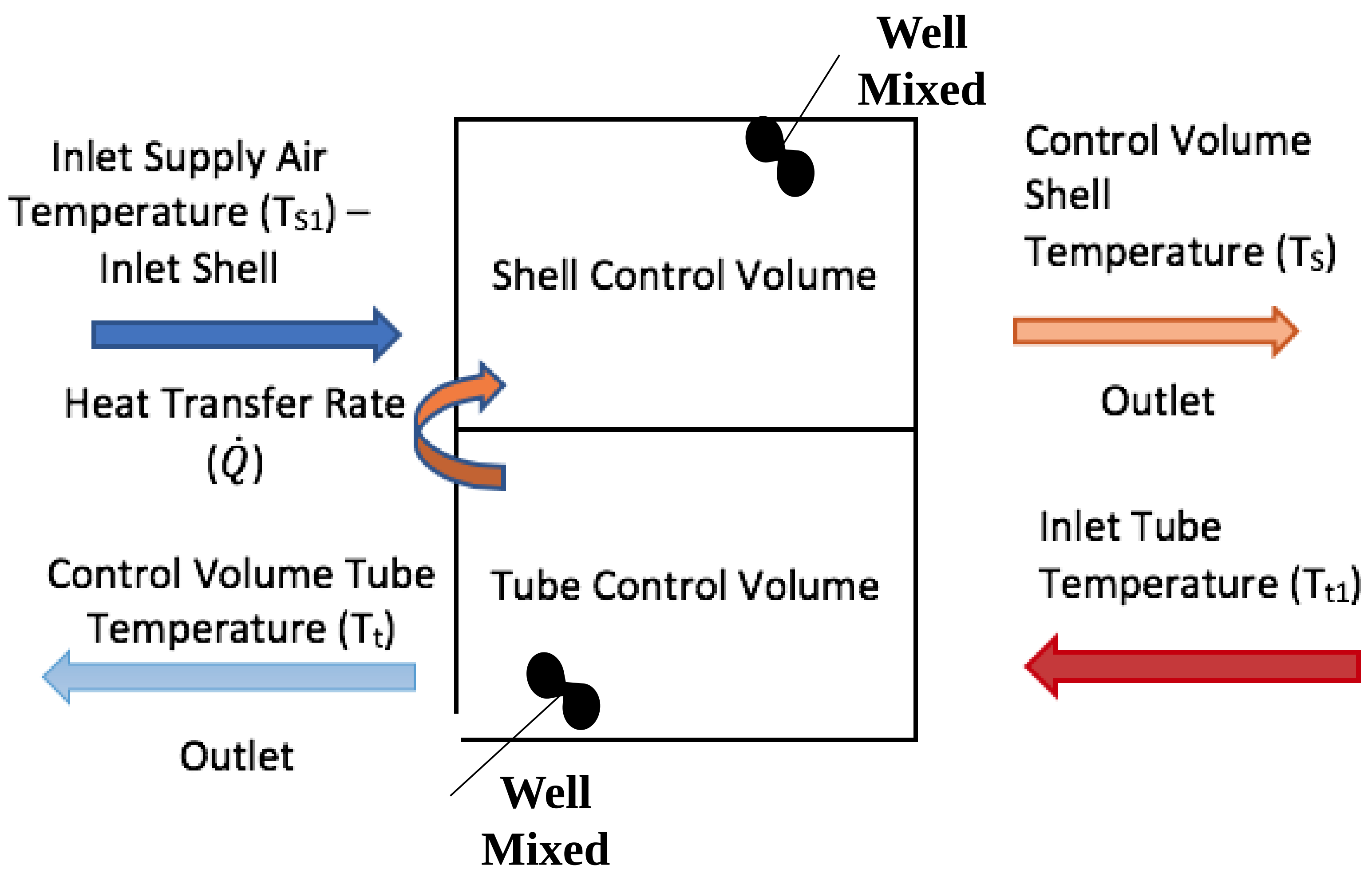


O2 Production System with Heat Recovery



Addition of Heat Recovery Unit

Simple HX Model



Design Constraints and Assumptions

- Treat shell and tube sides as two separate control volumes
- Well-insulated heat exchanger
- Well–mixed control volumes = Control Volume temperature is the same as outlet temperature.
- Fully developed flows.
- No mass accumulation in control volume = Steady state mass flows.
- Constant and low conduction resistance.
- Uniform, constant fluid properties on shell and tube sides.
- No external work on the system.
- Hot fluid in the tubes.
- Counter current flow configuration.

Mass Balance

- General Mass Balance

$$\frac{dm}{dt} = \sum \dot{m}_1 - \sum \dot{m}_2$$

- Mass Flow Rate of Shell = $\dot{m}_s$

$$\dot{m}_s = 3.95x10^{-4}\frac{kg}{s}$$

- Mass Flow Rate of Tube = $\dot{m}_t$

$$\dot{m}_t = 9.86x10^{-5}\frac{kg}{s}$$

Fluid Properties

Shell	Inlet Fluid Properties	Control Volume Fluid Properties
Specific Heat (*Cp)* [kJ/kgK]	1.006	1.089
Temperature (*T*) [°C]	25	117

Tube	Inlet Fluid Properties	Control Volume Fluid Properties
Specific Heat (*Cp)* [kJ/kgK]	1.154	1.089
Temperature (*T*) [°C]	519	117

Constants	
Convection Coefficient (U_o) [W/m^2K]	0.12
Surface Area (A_o) [m^2]	0.58
Mass of Fluid in Shell (m_s) [kg]	0.0049
Mass of Fluid in Tubes (m_t) [kg]	0.0014

Energy Balance - Heat

- General Energy Balance

$$\frac{\mathrm{d}(mCp(T-Tref))}{dt}=\sum \dot{m}_1\cdot h_1-\sum \dot{m}_2\cdot h \quad +\dot{Q}-\dot{W}$$

- Heat Transfer Rate ($\dot{\boldsymbol{Q}}$)
  - $\dot{\boldsymbol{Q}}$=*UA(AMTD)*
  - Arithmetic Mean Temperature Difference (AMTD)

$$AMTD=\frac{T_{t1}+T_t}{2}-\frac{T_{s1}+T_s}{2}$$

- Enthalpy rate ($\dot{m}h$)
  - $\dot{m}h=\dot{m}Cp\Delta T$
- External Work ($\dot{\boldsymbol{W}}$)
  - $\dot{W}$ =0

Energy Balance

- Shell and Tube Dynamic Model (DM)

  – Tube Energy Balance

$$\frac{dT_t}{dt} = \frac{\dot{m}_t \cdot Cp_{t1}}{m_t \cdot Cp_t}\left(T_{T1} - T_{ref}\right) - \frac{\dot{m}_t}{m_t}\left(T_t - T_{ref}\right) - \frac{U_o A_o}{m_t \cdot Cp_t}\left(\frac{T_{t1} + T_t}{2} - \frac{T_{s1} + T_s}{2}\right)$$

  – Shell Energy Balance

$$\frac{dT_s}{dt} = \frac{\dot{m}_s \cdot Cp_{s1}}{m_s \cdot Cp_s}\left(T_{S1} - T_{ref}\right) - \frac{\dot{m}_s}{m_s}\left(T_s - T_{ref}\right) + \frac{U_o A_o}{m_s \cdot Cp_s}\left(\frac{T_{t1} + T_t}{2} - \frac{T_{s1} + T_s}{2}\right)$$

Steady State

- Shell and Tube Steady State Model (SM)

  – Tube Energy Balance

$$0 = \frac{\dot{m}_t \cdot Cp_{t1}}{m_t \cdot Cp_t}\left(\overline{T_{t1}} - T_{ref}\right) - \frac{\dot{m}_t}{m_t}\left(\overline{T_t} - T_{ref}\right) - \frac{U_o A_o}{m_t \cdot Cp_t}\left(\frac{\overline{T_{t1}} + \overline{T_t}}{2} - \frac{\overline{T_{s1}} + \overline{T_s}}{2}\right)$$

  – Shell Energy Balance

$$0 = \frac{\dot{m}_s \cdot Cp_{s1}}{m_s \cdot Cp_s}\left(\overline{T_{s1}} - T_{ref}\right) - \frac{\dot{m}_s}{m_s}\left(\overline{T_s} - T_{ref}\right) + \frac{U_o A_o}{m_s \cdot Cp_s}\left(\frac{\overline{T_{t1}} + \overline{T_t}}{2} - \frac{\overline{T_{s1}} + \overline{T_s}}{2}\right)$$

Linearization and State Variables

- Shell and Tube DM – SM
  - Deviation State Variables

$\theta_1 = T_{t1} - \overline{T_{t1}} - T_{ref}$	$\theta_3 = T_{s1} - \overline{T_{s1}} - T_{ref}$
$\theta_2 = T_t - \overline{T_t} - T_{ref}$	$\theta_4 = T_s - \overline{T_s} - T_{ref}$

  - Tube Energy Balance

$$\frac{d\theta_2}{dt} = \frac{\dot{m}_t \cdot Cp_{t1}}{m_t \cdot Cp_t}(\theta_1) - \frac{\dot{m}_t}{m_t}(\theta_2) - \frac{U_o A_o}{m_t \cdot Cp_t}\left(\frac{\theta_1 + \theta_2}{2} - \frac{\theta_3 + \theta_4}{2}\right)$$

  - Shell Energy Balance

$$\frac{d\theta_4}{dt} = \frac{\dot{m}_s \cdot Cp_{s1}}{m_s \cdot Cp_s}(\theta_3) - \frac{\dot{m}_s}{m_s}(\theta_4) + \frac{U_o A_o}{m_s \cdot Cp_s}\left(\frac{\theta_1 + \theta_2}{2} - \frac{\theta_3 + \theta_4}{2}\right)$$

State Space (MISO)

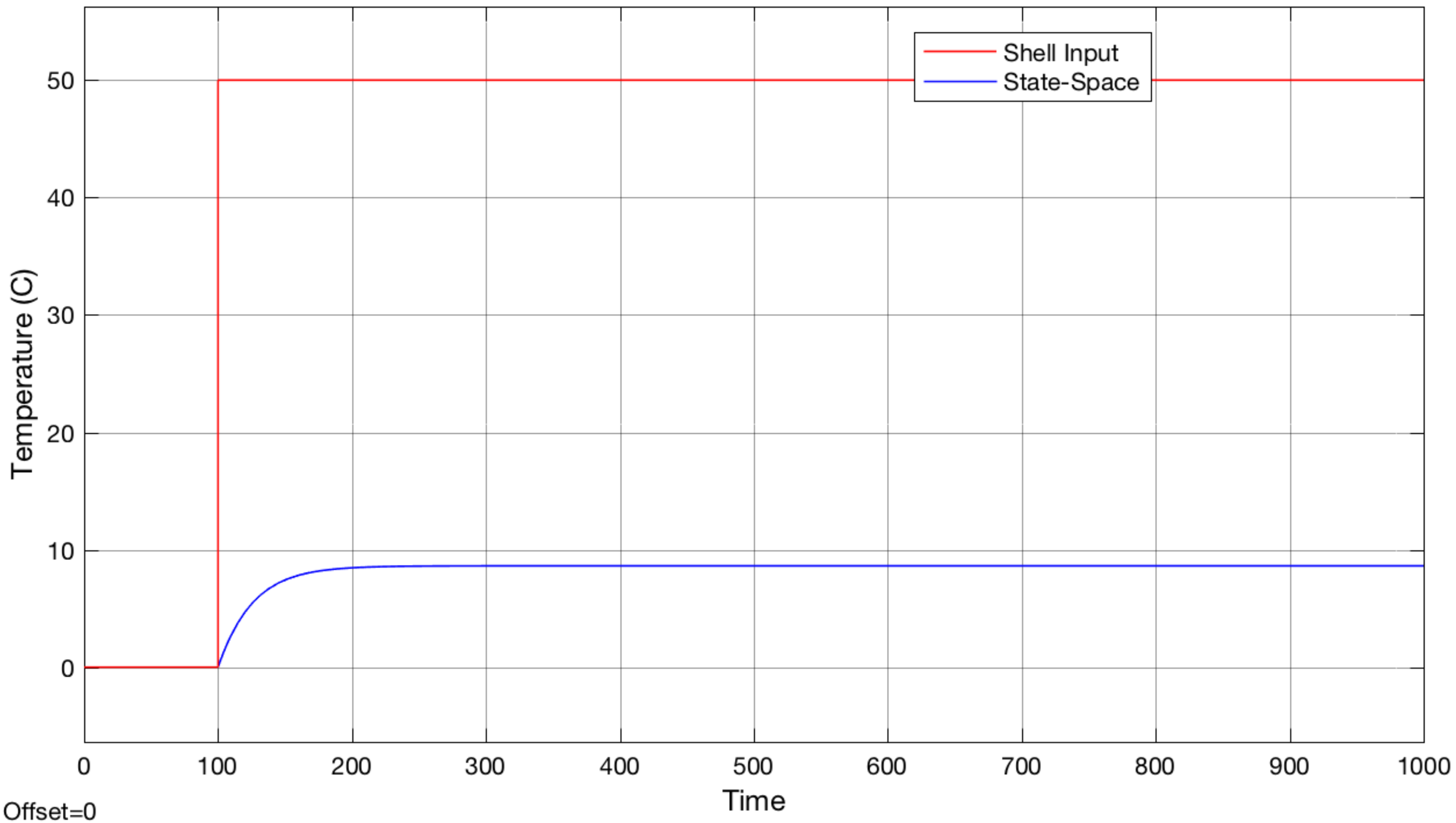
$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

$$\begin{bmatrix} \dot{\boldsymbol{\theta}}_4 \\ \dot{\boldsymbol{\theta}}_2 \end{bmatrix} = \begin{bmatrix} -\frac{U_o A_o}{2m_s Cp_s} - \frac{\dot{m}_s}{m_s} & \frac{U_o A_o}{2m_s Cp_s} \\ \frac{U_o A_o}{2m_t Cp_t} & -\frac{U_o A_o}{2m_t Cp_t} - \frac{\dot{m}_t}{m_t} \end{bmatrix} \begin{bmatrix} \boldsymbol{\theta}_4 \\ \boldsymbol{\theta}_2 \end{bmatrix} + \begin{bmatrix} -\frac{U_o A_o}{2m_s Cp_s} + \frac{\dot{m}_s Cp_{s1}}{m_s Cp_s} & \frac{U_o A_o}{2m_s Cp_s} \\ \frac{U_o A_o}{2m_t Cp_t} & -\frac{U_o A_o}{2m_t Cp_t} + \frac{\dot{m}_t\, Cp_{t1}}{m_t Cp_t} \end{bmatrix} \begin{bmatrix} \boldsymbol{\theta}_3 \\ \boldsymbol{\theta}_1 \end{bmatrix}$$

$$y = \boldsymbol{\theta}_4 = [1 \quad 0] \begin{bmatrix} \boldsymbol{\theta}_4 \\ \boldsymbol{\theta}_2 \end{bmatrix} + \mathbf{0} \begin{bmatrix} \boldsymbol{\theta}_3 \\ \boldsymbol{\theta}_1 \end{bmatrix}$$

Open Loop Response



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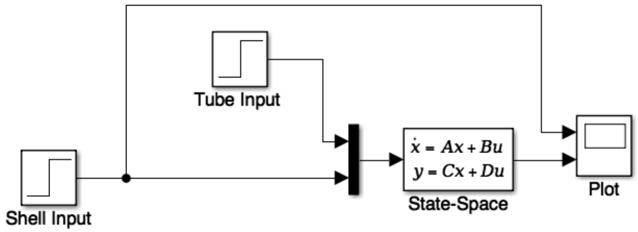
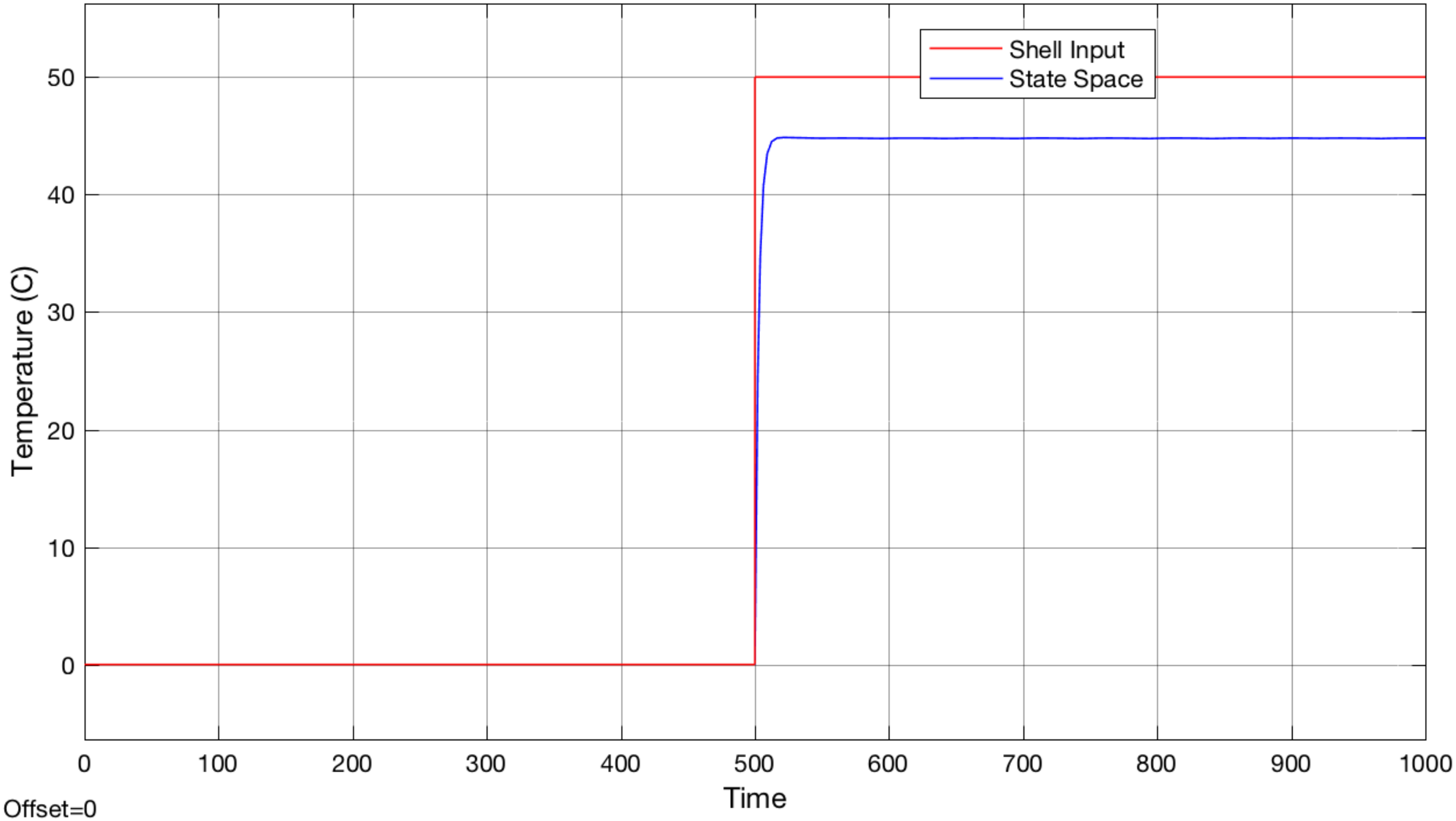


Control Design Requirements

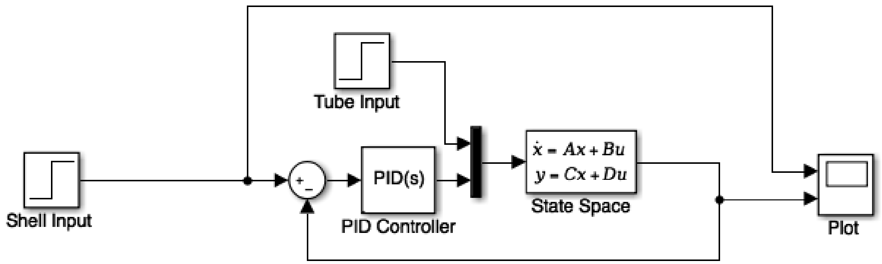
- No overshoot.
- 2% Steady State Error or less.
- No rapid change in temperature.
- Steady State in less than 3 hours

Closed Loop Response

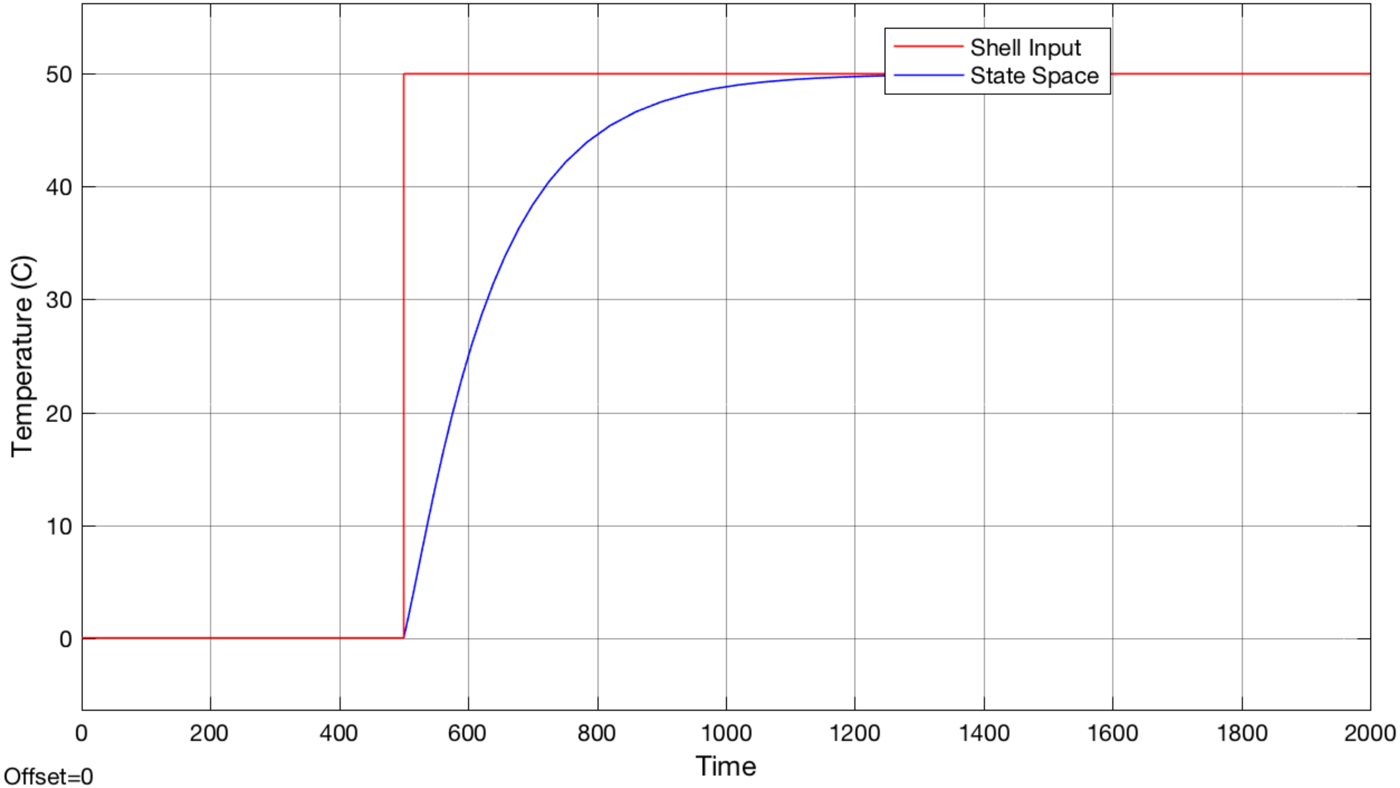


Offset=0

Controller	Value
P	50
I	0
D	0

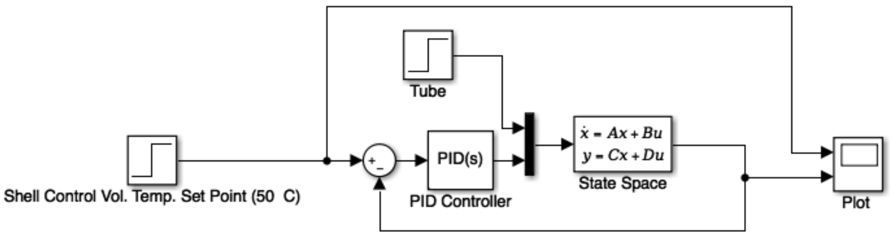


Closed Loop Response

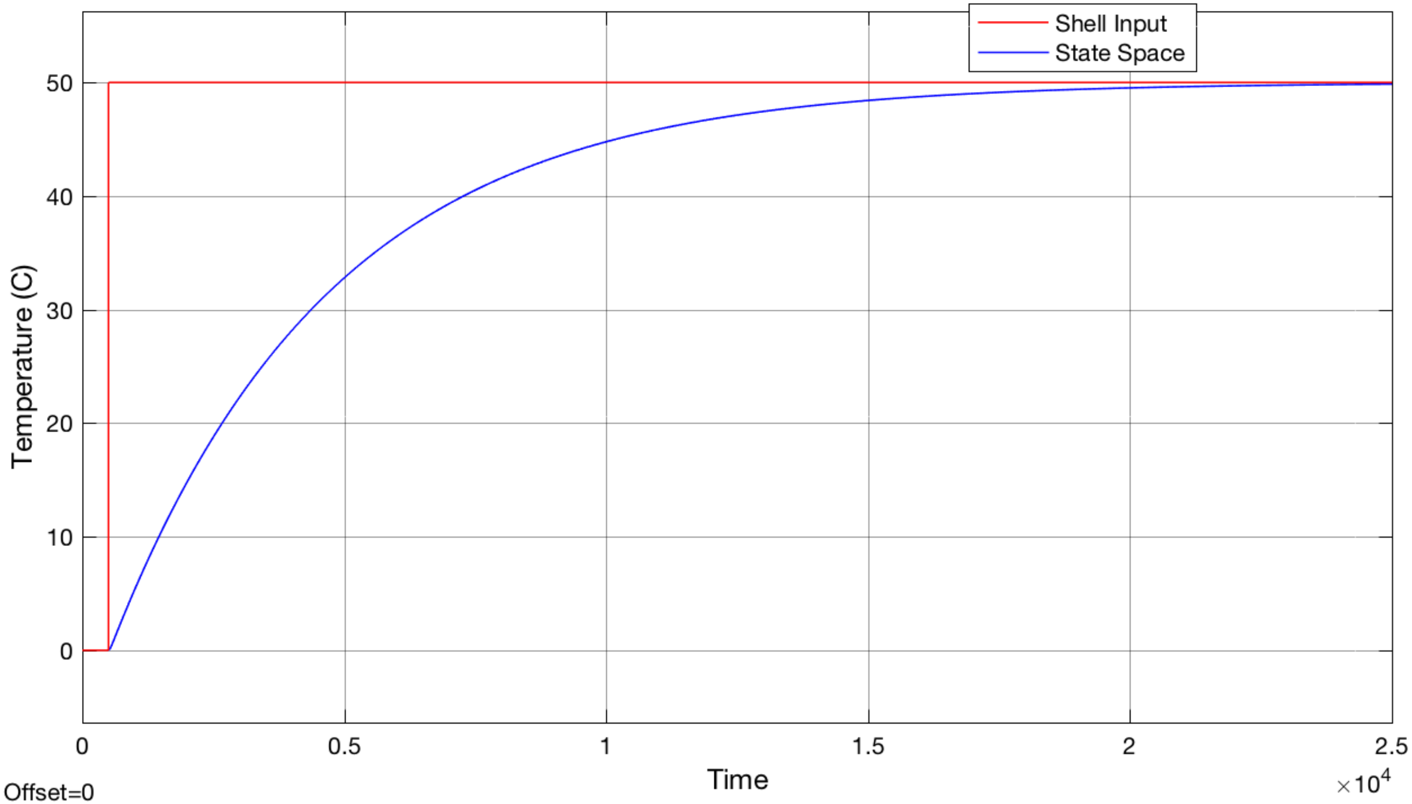


Offset=0

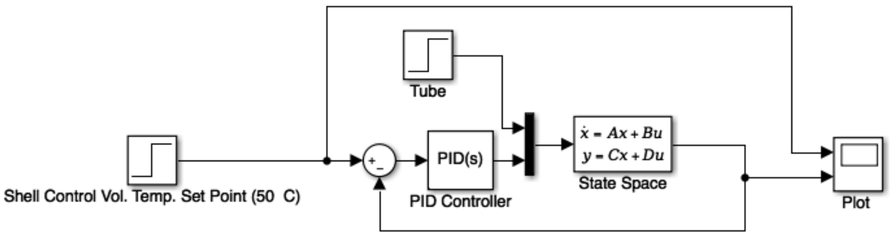
Controller	Value
P	0.747
I	0.042
D	0



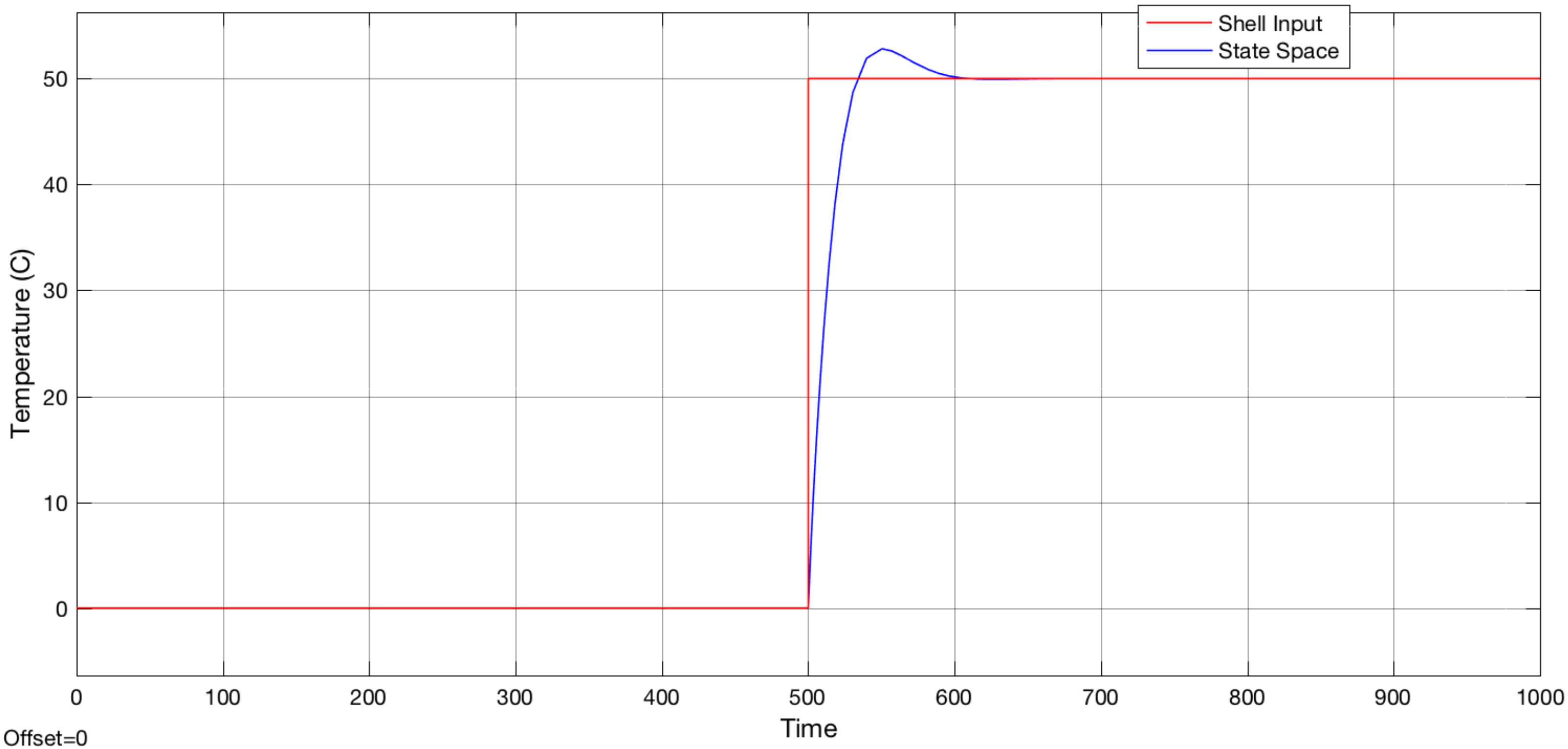
Closed Loop Response



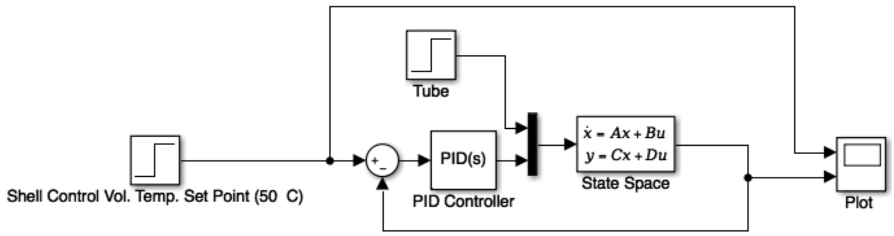
Controller	Value
P	0
I	0.00137
D	0



Closed Loop Response



Controller	Value
P	8.86
I	0.603
D	0.39



Conclusion

- A Heat Exchanger designed for Heat Recovery in High Temperature Oxygen Production System was analyzed
- A Simplified Dynamic model was developed to approximate the outlet shell temperature
- PID Controller is designed to ensure outlet shell temperature is maintained at given setpoint
- Based on the tuning, desired requirements including settling time can be achieved.

References

- Janna, William S., and Raj P. Chhabra. *Design of Fluid Thermal Systems*. Cengage Learning, 2015.
- Ogata, Katsuhiko. *System Dynamics*. Prentice Hall, 1998.
- Engineering ToolBox, (2005). *Dry Air Properties*. [online] Available at: https://www.engineeringtoolbox.com/dry-air-properties-d_973.html

Thank you

Appendix – Steady State Temperature

Shell

$$\frac{dE_S}{dt} = m_S * Cp_{S2} * \frac{dT_{S2}}{dt} = \dot{m}_S\left(Cp_{S1}(T_{S1} - T_r) - Cp_{S2}(T_{S2} - T_r)\right) + \frac{U_o * A_0}{2} * \left(T_{T1} + T_{T2} - (T_{S1} + T_{S2})\right)$$

Tube

$$\frac{dE_T}{dt} = m_T * Cp_{T2} * \frac{dT_{T2}}{dt} = \dot{m}_T\left(Cp_{T1}(T_{T1} - T_r) - Cp_{T2}(T_{T2} - T_r)\right) - \frac{U_o * A_0}{2} * \left(T_{T1} + T_{T2} - (T_{S1} + T_{S2})\right)$$

Steady State Shell (SSS)

$$0 = \dot{m}_S\left(Cp_{S1}(\overline{T_{S1}} - T_r) - Cp_{S2}(\overline{T_{S2}} - T_r)\right) + \frac{U_o * A_0}{2} * \left(\overline{T_{T1}} + \overline{T_{T2}} - (\overline{T_{S1}} + \overline{T_{S2}})\right)$$

Steady State Tube (SST)

$$0 = \dot{m}_T\left(Cp_{T1}(\overline{T_{T1}} - T_r) - Cp_{T2}(\overline{T_{T2}} - T_r)\right) - \frac{U_o * A_0}{2} * \left(\overline{T_{T1}} + \overline{T_{T2}} - (\overline{T_{S1}} + \overline{T_{S2}})\right)$$

SSS – SST

$$0 = \dot{m}_S\left(Cp_{S1}(\overline{T_{S1}} - T_r) - Cp_{S2}(\overline{T_{S2}} - T_r)\right) + \dot{m}_T\left(Cp_{T1}(\overline{T_{T1}} - T_r) - Cp_{T2}(\overline{T_{T2}} - T_r)\right)$$

$$\dot{m}_S\left(Cp_{S1}(\overline{T_{S1}} - T_r)\right) + \dot{m}_T\left(Cp_{T1}(\overline{T_{T1}} - T_r)\right) = \dot{m}_S\left(Cp_{S2}(\overline{T_{S2}} - T_r)\right) + \dot{m}_T\left(Cp_{T2}(\overline{T_{T2}} - T_r)\right)$$

$$\dot{m}_S\left(Cp_{S1}(\overline{T_{S1}} - T_r)\right) + \dot{m}_T\left(Cp_{T1}(\overline{T_{T1}} - T_r)\right) + (\dot{m}_S * Cp_{S2} + \dot{m}_T * Cp_{T2})T_r = \dot{m}_S\left(Cp_{S2}(\overline{T_{S2}})\right) + \dot{m}_T\left(Cp_{T2}(\overline{T_{T2}})\right)$$

$$\frac{\dot{m}_S\left(Cp_{S1}(\overline{T_{S1}} - T_r)\right) + \dot{m}_T\left(Cp_{T1}(\overline{T_{T1}} - T_r)\right) + (\dot{m}_S * Cp_{S2} + \dot{m}_T * Cp_{T2})T_r}{\dot{m}_S(Cp_{S2}) + \dot{m}_T(Cp_{T2})} = \overline{T_{T2}} = \overline{T_{S2}}$$