MODEL AND PRECISE CONTROL OF HEAT EXCHANGER

LI HONG RONG

May 7, 2019

National Cheng Kung University

Steady State Analysis Of Heat Load

Facility water loop	
Work fluid	Facility water from an open loop or a closed loop
Flow rate temperature	11.4LPM at 10° C 15.0LPM at 18° C 20.5LPM at 25° C
Pressure drop	$<$ 0.7 bar at 11.4LPM $<$ 1.7 bar at 20.5LPM
Adjusting time	$\leq$ 30 seconds(Mixing valve time)
Device	Temperature sensor, pressure gauge flow meter for water input

Steady State Analysis Of Heat Load- Continue

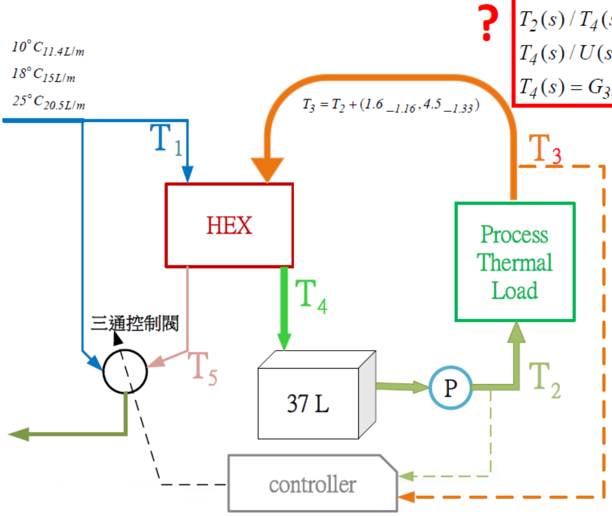
Process water loop	
Work fluid	Distilled water
Discharge temperature	$\pm 2^\circ$ C(with accuracy $\pm 0.25^\circ$ C)
Water delivery	"ON" mode: 79$\pm$4.5LPM / 3.7$\pm$0.1 bar "Standby" mode: 68$\pm$5.5LPM / 2.8$\pm$0.2 bar
Device	Temperature sensor $\times$ 2 for water delivery and return Water level switch for water level
Cooling capacity	Heat load can vary between 7.7 and 25KW

Steady State Analysis Of Heat Load- Continue

- 1KJ/s = 0.239kcal/s
- Heat Load
  - Standby Mode: 7.7kW
    7.7 KJ/s = 1.84 kcal/s
    70 LPM = 1.13 L/s
    temperature increase at the output of the load: 1.63°C
  - On Mode: 25kW
    25 KJ/s = 5.975 kcal/s
    79 LPM = 1.32 L/s
    temperature increase at the output of the load: 4.53°C
  - Temperature difference bewtween two mode: 2.9°C
- SB/ON mode switching time constant and time delay to be determined

Dynamic Model Of HEX

$$T_3(s)\,/\,T_2(s)$$
$$T_2(s)\,/\,T_4(s)$$
$$T_4(s)\,/\,U(s)$$
$$T_4(s) = G_{34}T_3(s) + G_{14}T_1(s) + GU(s)$$



To control T2,
a good regulating of T4 is required.
T1 and T3 can be considered as disturbances to T4.
The opening of the 3-way valve U is the control variable.

Dynamic Model Of HEX- Continue

- Process water output temperature(T_4)
  $m_p c_v \dot{T}_4 = m \times c_v(T_3 - T_4) - \frac{1}{R}(\frac{T_3+T_4}{2} - \frac{T_1+T_5}{2})$
- Facility water output temperature(T_5)
  $m_f c_v \dot{T}_5 = m_t \times c_v(T_1 - T_5) - \frac{1}{R}(\frac{T_1+T_5}{2} - \frac{T_3+T_4}{2})$
- Heat carried by Facility water

  $$m_t \times c_v(T_5 - T_1)$$

- m : process mass flow rate
  m_p : process water in HEX
  m_f : facility water in HEX
  m_t : 3-way valve mass flow rate

Reservoir Dynamic Model

- Resevoir volume: 37L
- $$\dot{T}_2 = \frac{(37 - \text{flow rate})\, T_2 + (\text{flow rate})\, T_4}{37} - T_2$$
  $$= \frac{\text{flow rate}}{37}(T_4 - T_2)$$
- time constant and time delay to be determined

Input-Output Relations

- Control variable: T_1, δT, v (opening of 3-way valve)
- Disturbance:
  ✓ δT due to heat emission of the process,
  $T_3 = (T_2 + \delta T)(1 - e^{-0.8t})$
  $\delta T = [1.63\ 4.53]$
- System States: T_5(not available), T_4, T_2
- System output: T_2
- Data for modeling
  - Effect of valve opening($0 \sim 1$)
  - Effect of T_1(facility water)
  - Effect of δT(operation mode SB/ON)

Data Plot- 1

We would like to observe the change of T_2 with the input vlave

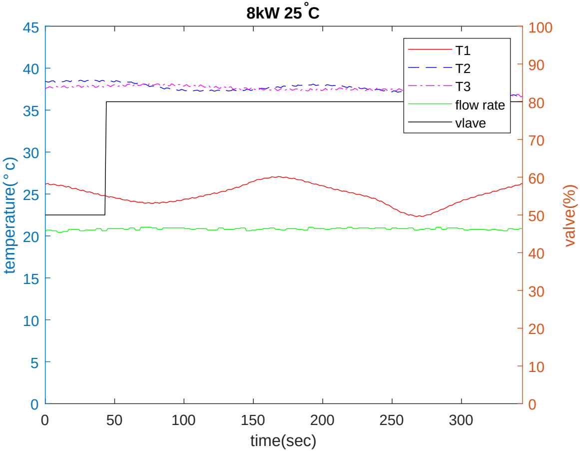


Figure 1: Heat load:8kW; T_1:25°C

Data Plot- 2

We would like to observe the change of T_2 with the input vlave

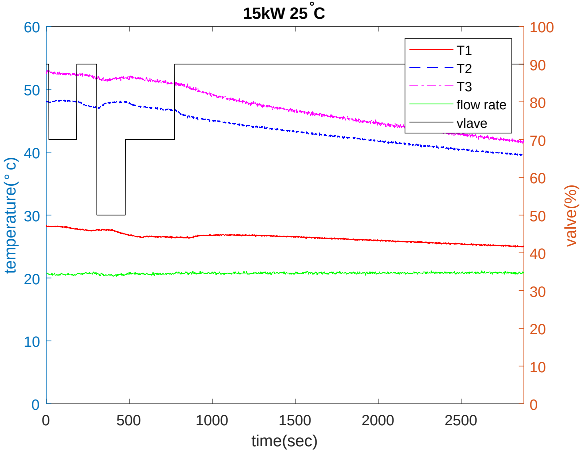


Figure 2: Heat load:15kW; T_1:25°C

Data Plot- 3

We would like to observe the change of T_2 with the input vlave

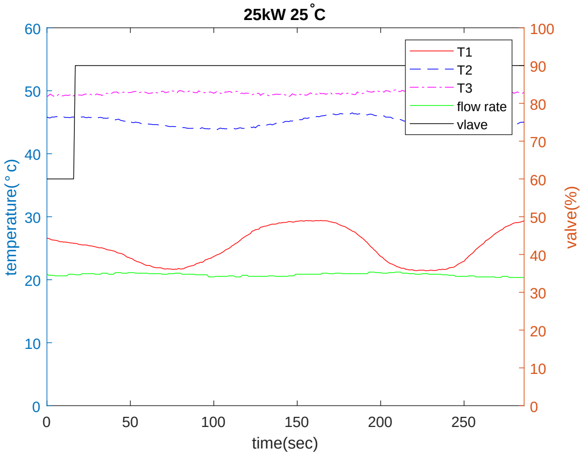


Figure 3: Heat load:25kW; T_1:25°C Part 1

Data Plot- 4

We would like to observe the change of T_2 with the input vlave

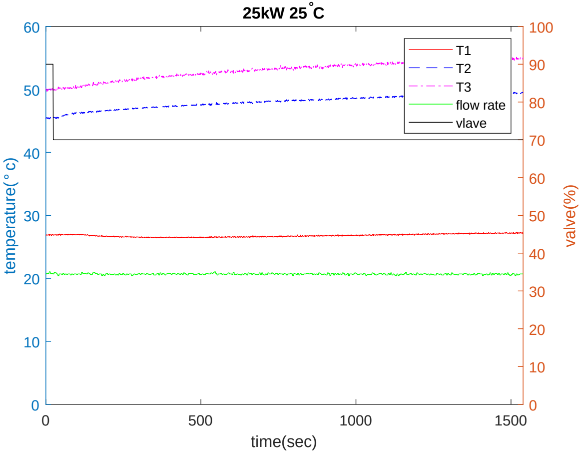


Figure 4: Heat load:25kW; T_1:25°C Part 2

Data Plot- 5

We would like to observe the change of T_2 with the input vlave

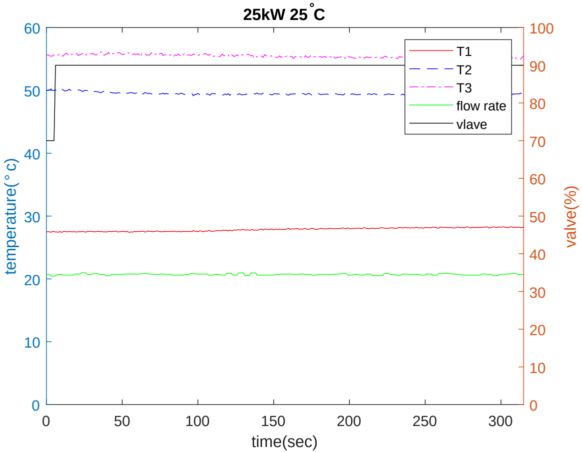


Figure 5: Heat load:25kW; T_1:25°C Part 3

Reservoir Dynamic ID

To find the model of reservoir, I use Figure 4 to analyze.
I simulate the system with the following condition

- delay 4 sec; one pole; none zero
- delay 5 sec; one pole; none zero
- delay 6 sec; one pole; none zero
- delay 5 sec; two poles; none zero

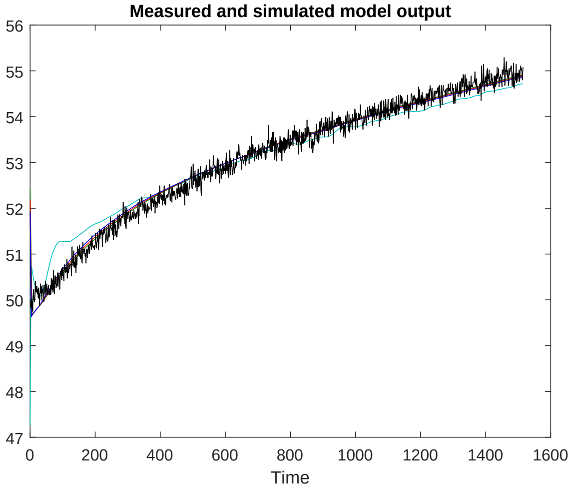


Figure 6: Reservoir ID

- The best fit result is $e^{-5s}\frac{0.01101}{s+0.009888}$

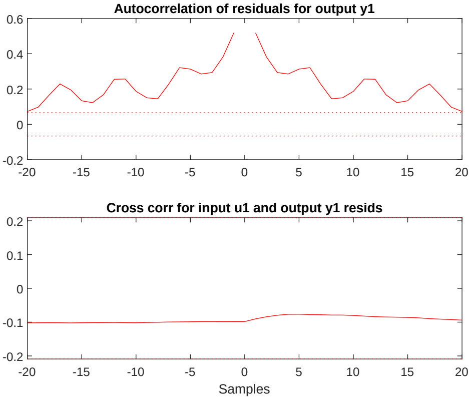


Figure 7: Reservoir ID Error

Linearization Of Dynamics

$$
\begin{aligned}
\Delta \dot{T}_2 &= -\frac{\text{flow}}{37}\Delta T_2 + \frac{flow}{37}\Delta T_4 && (1)\\
\Delta \dot{T}_4 &= (\frac{m}{m_p} - \frac{1}{2Rm_pc_v})(1 - e^{-0.8t})\Delta T_2 \\
&\quad + (-\frac{m}{m_p} - \frac{1}{2m_pc_vR})\Delta T_4 + \frac{1}{2m_pc_vR}\Delta T_5 \\
&\quad + \frac{1}{2Rm_pc_v}\Delta T_1 + (\frac{m}{m_p} - \frac{1}{2Rm_pc_v})(1 - e^{-0.8t})\Delta\delta T && (2)\\
\Delta \dot{T}_5 &= \frac{(1 - e^{-0.8t})}{2Rm_fc_v}\Delta T_2 + \frac{1}{2Rm_fc_v}\Delta T_4 \\
&\quad + (-\frac{mv_0}{m_f} - \frac{1}{2Rm_fc_v})\Delta T_5 + (\frac{mv_0}{m_f} - \frac{1}{2Rm_fc_v})\Delta T_1 \\
&\quad + \frac{(1 - e^{-0.8t})}{2Rm_fc_v}\Delta\delta T + \frac{m(T_{10} - T_{50})}{m_f}\Delta v && (3)
\end{aligned}
$$

Linearization Of Dynamics - Continue

where $\Delta x = [\Delta T_2 \, \Delta T_4 \, \Delta T_5]^T$, $\Delta u = [\Delta T_1 \, \Delta\delta T \, \Delta v]^T$
with operating point $[T_{20} \; T_{40} \; T_{50} \; T_{10} \, \delta T_0 \; v_0]$

State Space Model

Combine equation(1) (2) (3)

$$\begin{bmatrix} \Delta \dot{T}_2 \\ \Delta \dot{T}_4 \\ \Delta \dot{T}_5 \end{bmatrix} = \begin{bmatrix} -\frac{\text{flow}}{37} & \frac{flow}{37} & 0 \\ (\frac{m}{m_p} - \frac{1}{2Rm_pc_v})(1-e^{-0.8t}) & (-\frac{m}{m_p} - \frac{1}{2Rm_pc_v}) & \frac{1}{2Rm_pc_v} \\ \frac{(1-e^{-0.8t})}{2Rm_fc_v} & \frac{1}{2Rm_fc_v} & (-\frac{mv_0}{m_f} - \frac{1}{2Rm_fc_v}) \end{bmatrix} \begin{bmatrix} \Delta T_2 \\ \Delta T_4 \\ \Delta T_5 \end{bmatrix}$$
$$+ \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{2Rm_pc_v} & (\frac{m}{m_p} - \frac{1}{2Rm_pc_v})(1-e^{-0.8t}) & 0 \\ (\frac{mv_0}{m_f} - \frac{1}{2Rm_fc_v}) & \frac{(1-e^{-0.8t})}{2Rm_fc_v} & \frac{m(T_{10}-T_{50})}{m_f} \end{bmatrix} \begin{bmatrix} \Delta T_1 \\ \Delta \delta T \\ \Delta v \end{bmatrix} \tag{4}$$

$$\Delta y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta T_2 \\ \Delta T_4 \\ \Delta T_5 \end{bmatrix} \tag{5}$$

Equilibrium point

Make the R.H.S of nonlinear differential equation to be zero

$T_{10} = T_{50} = T_{40} = T_{20}$, $\delta T_0 = 0$, v_0 can be arbitrary number

Choose $T_{10} = T_{50} = 25^\circ\mathrm{C}$