Exercise 1

1 Control of mixer and reactor process

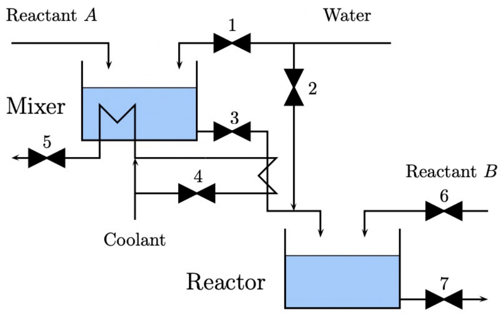


Figure 1: Control of mixer/reactor process

The process flowsheet is shown in Figure 1. Pure reactant A is fed to a mixer where it is diluted with (pure) water to a specific concentration. The flowrate of reactant A entering the mixer can be measured. The concentration of reactant A in the mixer cannot be measured because it is difficult to install a concentration sensor in the mixer due its complex internal design. Mixing of A with water is an exothermal process (heat is released) resulting in a increase of the temperature, and cooling is needed to keep the temperature below a certain limit. The outlet flow of the tank is further cooled in a heat exchanger. The concentration of the flow going from the mixing tank to the reactor is "fine tuned" by adding more water. It is possible to measure the concentration of the flow entering the reactor. Reactant B is fed into the reactor, where it reacts with reactant A. The reactor temperature should be kept constant.

a) Give the definition for *manipulated variable* (MV), *controlled variable* (CV) and *disturbance* (DV) (for a general process).

a) MV: Manipulated variables are variables we can adjust, usually to counteract disturbances to keep controlled variables at desired values

DV: Disturbances, variables we can't control

CV: Controlled variables, variables/outputs we want to control/keep at a desired level.

b) Identify and classify the variables for the process shown in Figure 1: *manipulated variables* (MVs), *controlled variables* (CVs) and important *disturbances* (DVs).

Assuming that reactant B is pure:

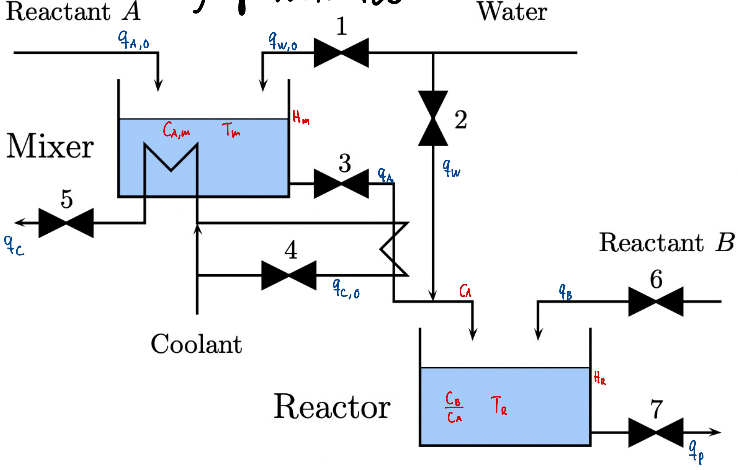
DV: Flow rate of reactant A, possibly also temperatures of inflows

CV: Concentration of A in inflow to reactor, temperature of the reactor, temperature in the mixer, liquid level in mixer, liquid level in reactor, concentration of B in reactor (relative to flowrate of A from mixer), ratio of A/water in mixer

MV: Valves 1-7 :
1 = pure water into mixer
2 = pure water mixed into outflow from mixer
3 = outflow from mixer
4 = cooling of outflow from mixer
5 = cooling of mixer
6 = flow rate of reactant B
7 = outflow from reactor

c) Suggest a control structure.
Hint: This process can be controlled by using five feedback controllers and two feedforward (ratio) controllers. To specify the feedback controllers, pair a CV with a MV.

Naming of variebles

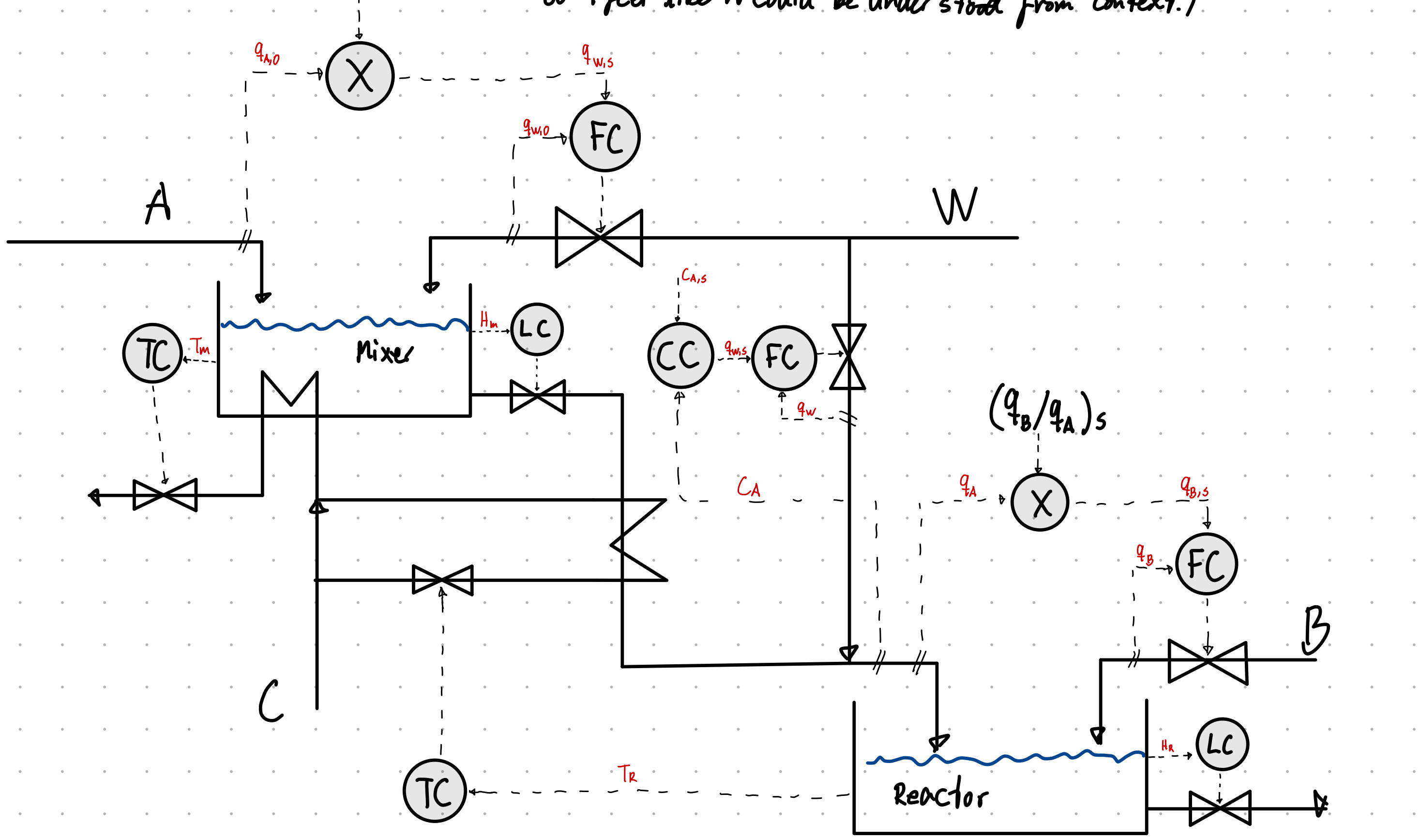


CV \ MV	$q_{w,0}$	q_w	q_A	$q_{c,0}$	q_c	q_B	q_p
$C_{A,m}$	−	0	0	0	0	0	0
T_m	(−)	0	0	0	−	0	0
H_m	+	0	−	0	0	0	0
C_A	(−)	−	(+)	0	0	0	0
C_B/C_A	0	0	−	0	0	+	0
T_R				−	(−)		0
H_R	(+)	(+)	+	0	0	+	−

● = feedback
● = feedforward

- Feed forward on the mixer and reactor, can't measure concentration in mixer, and as a reactor uses reactants, concentration measuring is not viable
- Using close pairing, the feedbacks are determined

- Control structure: $(q_{w,0}/q_{A,0})_s$ (not sure if I should have more or less FC, all parameters are flows, so I feel like it could be understood from context.)



2 Temperature control in a tank (similar to control of shower)

The feed to a continuous process enters through a long pipeline (Figure 2). We assume perfect mixing and constant volume in the tank (using level control). The heat loss is neglected. We want to analyze how the tank temperature (T) changes when the inlet temperature T_0 varies.

Note: In the following questions "green line" means that you should plot the behavior of the tank temperature (T) by hand by extending the green line in the plots in Figure 3.

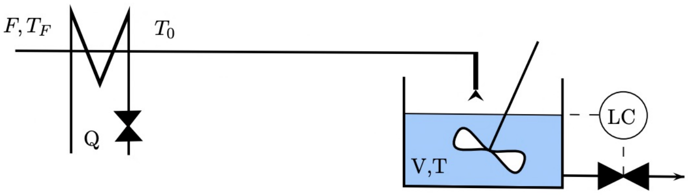


Figure 2: Pipe and tank process

Table 1: Data

parameter	symbol	value	unit
mass flow	(F)	10	$\mathrm{kg\,s^{-1}}$
water density	(ρ)	1000	$\mathrm{kg\,m^{-3}}$
pipe area	(A)	0.01	$\mathrm{m^2}$
pipe length	(L)	100	m
tank volume	(V)	0.2	$\mathrm{m^3}$

2.1 Dynamics

1. Formulate the dynamic energy balance for the tank (without the pipeline). In other words, find an expression for $\frac{dT}{dt}$.
   Assume: LC working perfectly (constant level), perfect mixing ($T_{out} = T$), $c_p = c_v$, constant c_p. Neglect motor power of the mixer and heat losses. **Note:** Check chapter 11 on "Process Dynamics" available on Blackboard for guidelines on mass and energy balances.

We know that: $h(T) = h(T_{ref}) + \int_{T_{ref}}^{T} C_p(T)\,dT$

Enthalpy balance

$$\frac{dH}{dt} = H_{in} - H_{out} + Q + W_s - (p_{ex} - p)\frac{dV}{dt} + V\frac{dp}{dt}$$

It is given that $W_s = 0$, $Q = 0$, $\frac{dV}{dt} = 0$ (perfect LC), $\frac{dp}{dt} = 0$ (assuming open tank as in figure)

We are left with:

$$\frac{dH}{dt} = H_{in} - H_{out}$$

There are no reaction and no phase transition

$$\Rightarrow\ m \cdot C_p(T)\frac{dT}{dt} = F_{in}\int_{T_{ref}}^{T_{in}} C_p(T)\,dT - F_{out}\int_{T_{ref}}^{T_{out}} C_p(T)\,dT$$

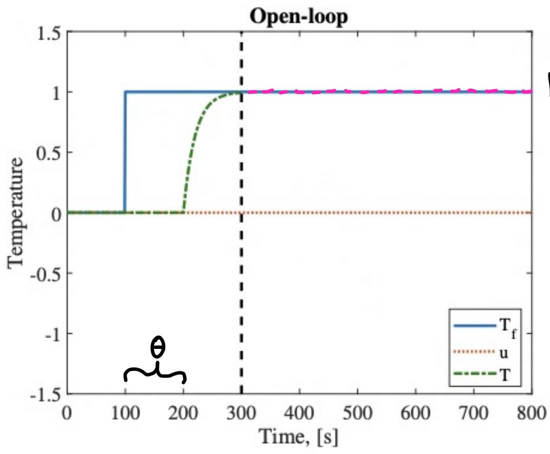
We have constant C_p, and as the level is constant, $F_{in} = F_{out} = F$

$$m\,\cancel{C_p}\,\frac{dT}{dt} = F \cdot \cancel{C_p} \cdot (T_{in} - \cancel{T_{ref}}) - F \cdot \cancel{C_p}(T_{out} - \cancel{T_{ref}})$$

$$m\frac{dT}{dt} = F(T_{in} - T_{out}) \quad , \ T_{out} = T;\ m = \rho V;\ T_{in} = T_0$$

$$\frac{dT}{dt} = \frac{F}{\rho V}(T_0 - T)$$

2. Sketch the time response in T to a step change in T_f when there is no control; so $T_0 = T_f$. Include the effect of a long pipeline in your reasoning.
Complete the green line in Figure 3a.



(a) Open-loop response

I used pink for visibility

- Due to the long pipeline there is a delay (Θ) before we see an effect of the change.
- The temperature will increase quickly in the beginning, and slow down when it approaches T_f, then the temperature will stabilize on T_f as there is no control to counteract the change.

3. Use the values in Table 1 to find the gain (k), time constant (τ) and delay (θ) for this process. Consider T_0 as input and T as output.

Delay: The time it will take for the water to travel through the entire pipe:

Volume flow: $q = \frac{F}{\rho} = \frac{10\ kg/s}{1000\ kg/m^3} = 0{,}01\ m^3/s$

The speed of the flow: $V = \frac{q}{A} = \frac{0{,}01\ m^3/s}{0{,}01\ m^2} = 1\ m/s$

Time to travel through the pipe: $\underline{\underline{\Theta = \frac{L}{V} = 100\ s}}$

Gain: $\underline{\underline{k = \frac{\Delta T(\infty)}{\Delta T_f} = 1}}$ (T and T_f will be equal at steady state, as long as Q is turned off)

Time constant: Rearranging the previously derived equation for $\frac{dT}{dt}$:

$$\frac{\rho V}{F}\frac{dT}{dt} = T_{in} - T$$

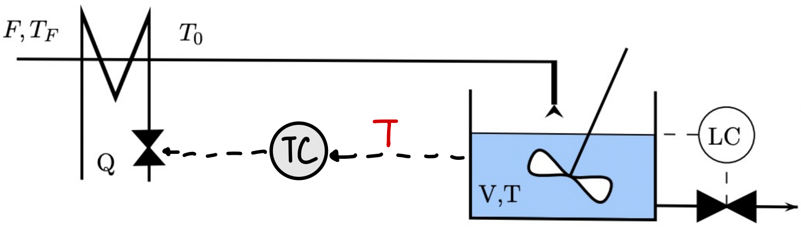
comparing this to the general equation $u = T_{in}$ and $y = T$:

$$\tau \frac{dy}{dt} = -y + ku$$

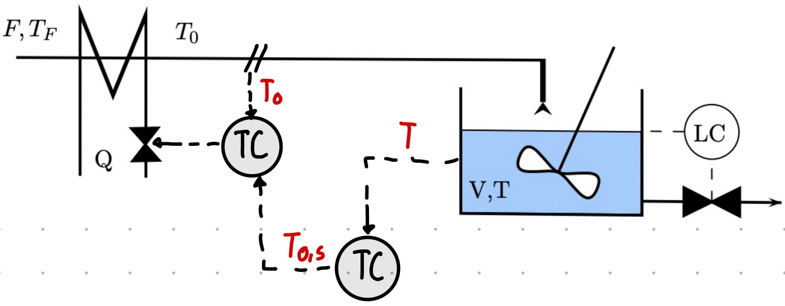
we see that $\underline{\underline{\tau = \frac{\rho V}{F} = \frac{1000 \cdot 0{,}2}{10} = 20\ s}}$

2.2 Control

1. In practice, we can adjust T using an electrical heater (Q). Draw a flowsheet and suggest how to control the temperature in the tank ($y = T$) using the heater with a single feedback controller.



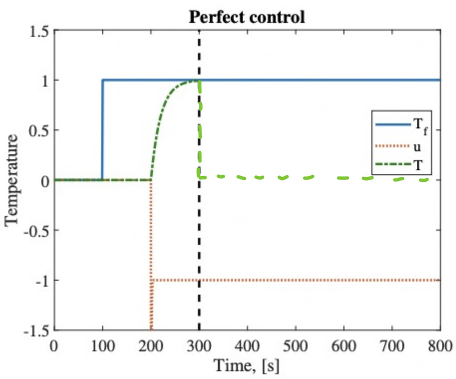
2. The time delay due to the long pipe can be a problem for good control of T. Suggest an improved control structure (with cascade) based on measuring also T_0. Comment: the outer cascade is intended, for example, to correct for possible heat loss in the pipe and in the tank.



3. Consider a step disturbance in T_F. Consider that the disturbance is at $t = 100$ s for this example.

   - What is the best possible control (ideal control) one can get for T for this system using feedback based on measuring T? Complete the green line in Figure 3b.
   - What if we can measure T_0?

Ideal control: Delayed detection of disturbance, immediately brings the system under control after detection (which will take in total t=20 due to delay in pipe)



(b) Perfect control

If we instead measure T_0, the controller detects the disturbance before the pipe, and can negate it before the temperature of the tank changes.

4. What if we can measure $T_F(d)$ and use feedforward control? What is the best possible?

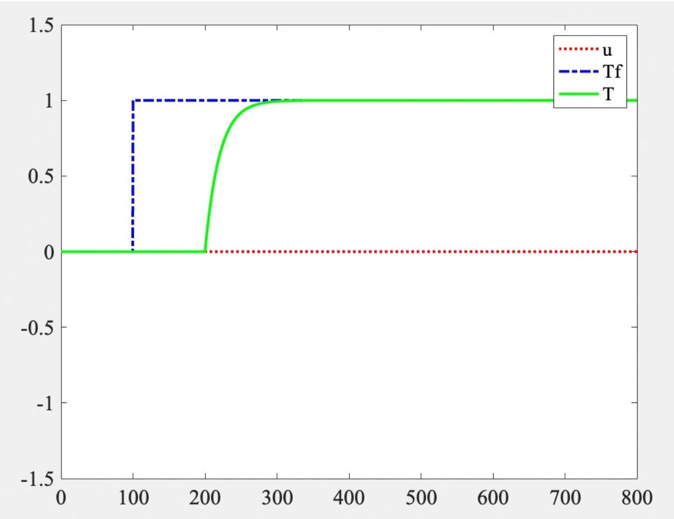
It should also be possible to counteract the disturbance so that the temperature in the tank is kept constant.

2.3 Simulation

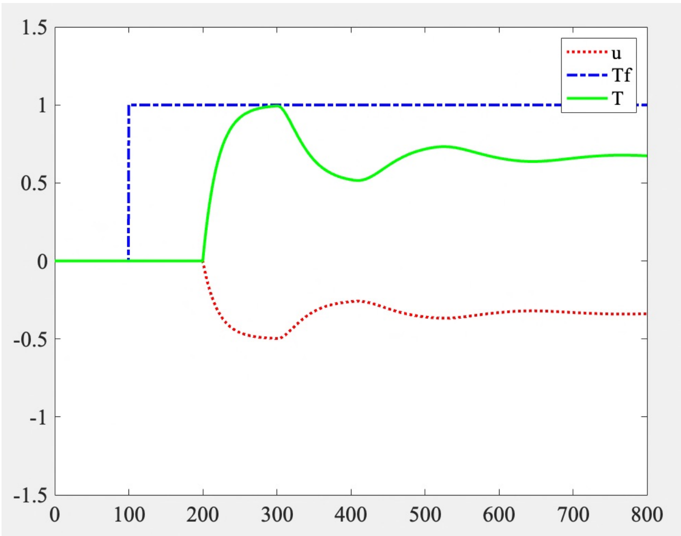
The rest of the exercises is not expected. We will cover this part in the Introduction to Matlab and Simulink lecture.
However, it is possible to do it if you follow the instructions below, even if you have never used Simulink.

Simulate case 1 with $y = T$ for a step disturbance (d) in T_F using a PI controller with gain K_c and integral time τ_I [s]. The input is the scaled heat input, $u = \Delta Q/(FC_p)$. Use the Simulink file `tunepid1_ex1` You can run this file using the example code in Listing 1.

1. No control (`Kc=0` which gives $u = 0$). Note that the result should be the same as in Task 2. Complete the green line in Figure 3a.

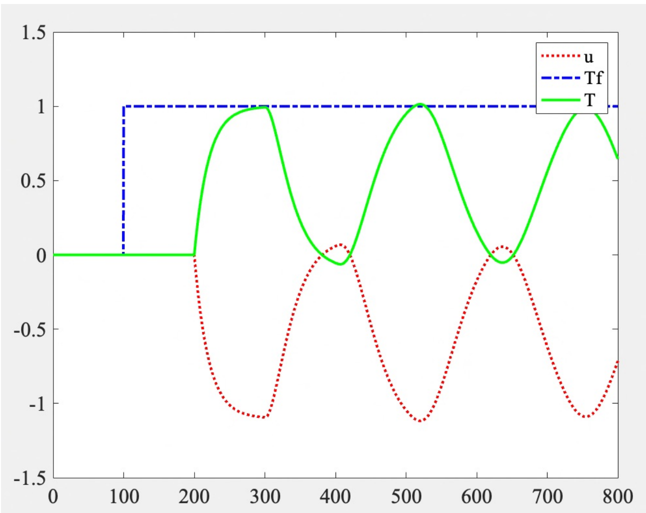


2. P-control (keep `taui=99999` at a large value so the I-action is off). Use `Kc=0.5`. Complete the green line in Figure 3c.



3. P-control. Try increasing `Kc`. At what value of `Kc` does the system go unstable? Can you explain this?

Looks like it becomes unstable at $K_c = 1,1$

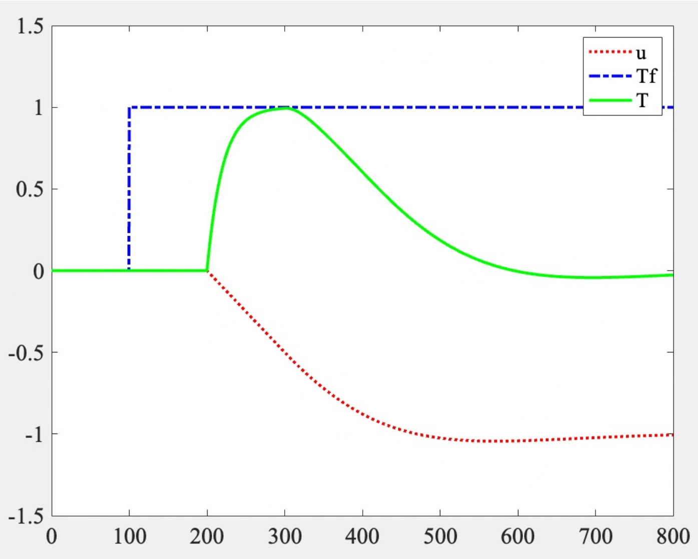


4. PI-control. Use SIMC rule with `tauc=delay`. Complete the green line in Figure 3d.

$$\tau_c = \theta = 100s, \quad \tau = 20s, \quad k = 1$$

$$K_c = \frac{1}{k} \cdot \frac{\tau}{\tau_c + \theta} = \frac{1}{1} \cdot \frac{20}{100+100} = \frac{20}{200} = 0{,}1$$

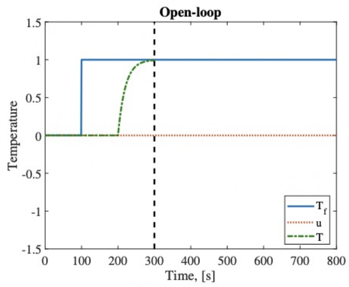
$$\tau_I = \min(\tau, 4(\tau_c + \theta)) = \min(20, 400) = 20$$



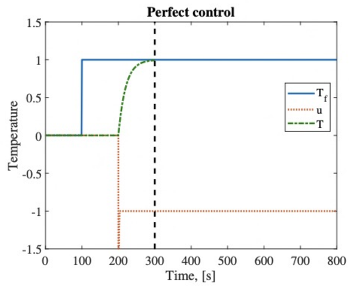
2.4 Figures

In Figure 3, the input u (scaled heat input; red line) and the disturbance T_f (blue line) are plotted for the whole simulation, but the output T (green line) is plotted to 300 s. Please sketch by hand the behavior of output T (green line) for the remaining time.

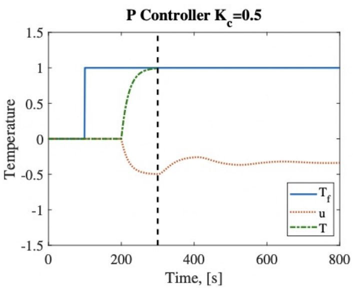
This has already been done in previous problems.



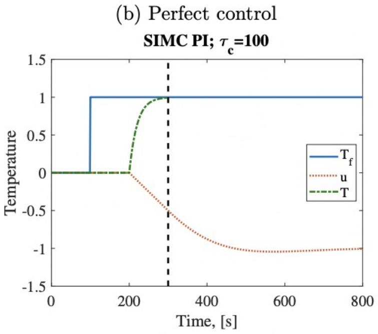
(a) Open-loop response



(b) Perfect control



(c) Proportional control



(d) Proportional-Integral control

Figure 3: Step response plots