Thermal Model Development and Control Design Interface of a PEM Fuel Cell for Simulation Based Learning in a Mechanical Engineering Course

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Abstract

Although there is growing interest in electrochemical systems such as battery and fuel cell powered vehicles, thermal fluid modeling and control design of such systems is not commonly taught. To incorporate such content, an educational learning software interface was developed for teaching classical process modeling and advance control design techniques in an undergraduate control theory course in mechanical engineering.

A fuel cell is an electrochemical energy conversion device that uses fuel to generate electricity. It basically converts the chemical energy of reactants directly into electricity without combustion. In a Proton Exchange Membrane Fuel Cell (PEMFC), the reactants, hydrogen and oxygen, are fed into the two electrodes, anode and cathode, respectively. As a result of the reactions, electricity is generated along with water and heat as by-products. In order to maximize performance of a fuel cell, many factors can be considered for tuning and control. Power and temperature management is one of these factors. A thermal-fluid model of a PEMFC has been developed combined with an existing electrochemical model to predict the voltage and temperature responses based on step input changes during open loop operation. The PEMFC stack model was developed using MATLAB and Simulink. The interface also allows to design control strategies using conventional PID controllers as well as advance control techniques to manage the PEMFC output responses. The input variables include flow rates while the stack temperature and voltage are output variables. The results show promise where the transient and steady state responses to change in a manipulated variable with and without controllers can be readily observed to help understand the relationship between a pair of input and output variables. Such an interface could open the door to other possibilities for students as they can conduct their own investigations of a fuel cell to expand their knowledge and skills.

Keywords

Fuel Cell, Control Theory, MATLAB, Simulink, Thermal Modeling

Introduction

Fuel cells convert chemical energy in fuels directly into electrical energy[1]. They are a promising power generation source with high efficiency and low environmental impact[2]. Although there has been significant amount of research conducted for this technology, there is limited course content with focus on thermal fluid aspects of the fuel cell in mechanical engineering courses[3]. Currently, in the Thermal Fluids Laboratory (TFL) course and technical elective course called Process Control (PC), the student learning objectives (SLO) include:

1. Ability to develop mathematical models and transfer functions of processes. (PC)
2. Analyze and model dynamic processes in time domain. (PC)
3. Utilize computational tools to design and analyze different types of control systems. (PC)
4. Able to read and interpret block diagrams, and process and instrumentation diagrams. (PC)
5. Apply heat transfer concepts for analysis of basic fluid mechanics experiments (TFL)
6. Apply fluid mechanics concepts for analysis of basic heat exchangers configurations (TFL)

Using these SLOs as a guide, the background and the interface development method will be presented.

In a proton exchange membrane fuel cell, hydrogen gas is fed to the negative electrode (anode) side of the fuel cell and oxygen from the air is fed into the positive electrode (cathode) side. Hydrogen gas reacts with a catalyst in the anode side and is broken down into protons and electrons. The protons pass through the membrane to the cathode side of the cell where they react with oxygen to form water. The electrons travel in an external circuit, generating the electrical output of the cell[1]. The reaction in a single fuel cell is illustrated in Figure 1.

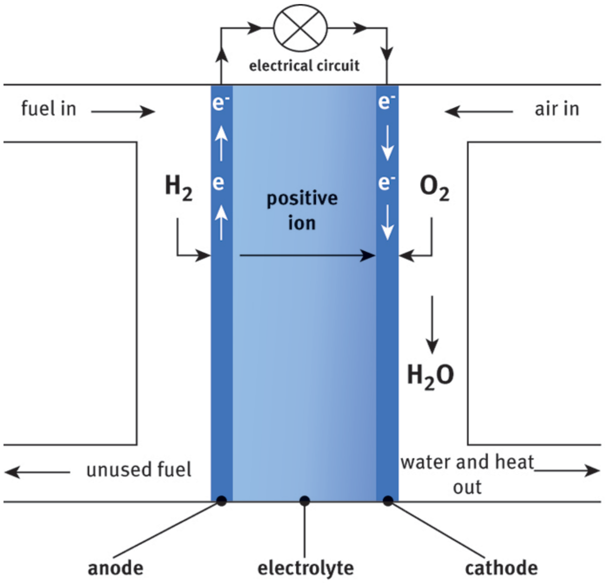


Figure 1. Diagram of Fuel Cell Reaction[4]

To be able to model the fuel cell, a computational software is chosen to effectively develop, analyze and control the thermal model of the PEMFC. A system-function (S-function) is generally described as a Simulink block that can be written in various languages such as C, C++, MATLAB and more in order to interact with the Simulink engine[5]. S-functions are utilized during nonlinear or dynamic modeling of systems as it allows for different aspects of a script to be modified for the benefit of the creator. For example, S-functions could be modified to have a variety of inputs, outputs, or initialization settings. This serves well for the dynamic modeling of the PEMFC, as the user could define the mathematical relationships between the input variables and the output variables along with the state space variables of the model. Assumptions for this PEMFC model for the built-in electrochemical model and additional thermal fluid model are fixed control volumes for each electrode channel, all gases are ideal, fluid flows are incompressible due to low flow rate and Mach number below 0.3, well-mixed fluids in each channel, no accumulation of mass in each channel, pure hydrogen is used as fuel, no phase change in the system, and air contains only nitrogen (78%), oxygen (21%), and water vapor (1%). This model also assumes that the maximum efficiency of the PEMFC achieved is 40%.

In order to actuate the fuel cell system to manipulate the input signal that results into the desired output, an actuating signal is generated. The fuel cell system output will be compared with the desired set point and the resultant error is sent back as a new input to the controller to adjust the system to maintain the desired output[6]. One way to control the system is to introduce a classical controller such as PID. The objective is to introduce a controller such that it helps maintain the stable system operation at the setpoint regardless of the change in the input variables of the system. The proportional controller scales the error until the system reaches the desired setpoint by increasing or decreasing the multiplier term or gain, an integral controller will be added to the path to remove the steady state error, and the derivative controller measures the rate of change of the error and predicts how much increase or decrease is being produced for the error. This type of feedback controller is very common for dynamic systems as it keeps track of the error and rate of error and compensates the system smoothly to maintain the setpoint[6]. The weight of each controller can be tuned for the final controller provide the most stable and reliable desired system responses.

With the completion and implementation of the model interface, students in the TFL course will be able to analyze the PEMFC channels in terms of concepts from fluid mechanics and heat transfer such as pressure drop, and steady state heat transfer rate and duty. With the completion and implementation of the control interface, students in the PC course will be able to:

1. Develop mathematical models of the PEMFC process by deriving from the mass and energy balance equations.
2. Properly read and interpret block diagrams
3. Relate the use of control systems to real-world applications

Thus, the students will be able to relate concepts learned in mechanical engineering courses to a more practical application of a fuel cell, which is a complex energy conversion system involving electrical, chemical, thermal and mechanical energies.

Methodology

The MATLAB GUI in Figure 2 is a built-in app that is used to interact with the system through graphical symbols and audio indicator instead of text-based user interfaces. The GUI displays current, voltage, power, hydrogen flow rate, and oxygen flow rate while allowing control over run time and voltage. Voltage in this case is the controlled variable while hydrogen flow rate is the manipulated variable. The desired voltage is selected within the allowable range and the system evaluates the amount of hydrogen and oxygen needed for it to be true. Restrictions were implemented to re-enact actual PEMFC limitations.

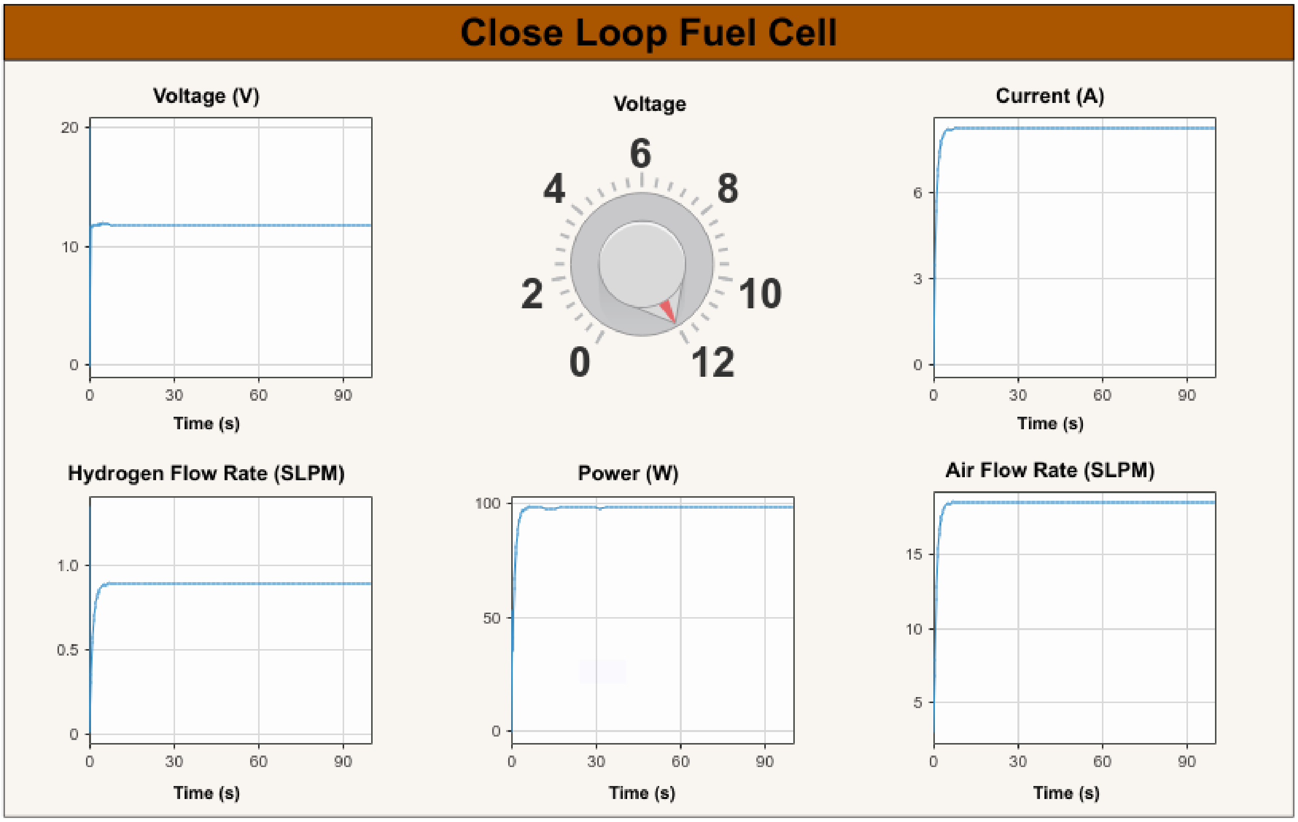


Figure 2. Interface of the PEMFC Simulation

The S-function was defined to have the following three inputs as shown in in Figure 3: The load current, the mass flow rate of hydrogen, and the mass flow rate of air that is sum of the nitrogen, oxygen, and water vapor flows and has composition of 78%, 21%, and 1%, respectively. The two outputs of the model were dictated to be that of the average temperature of the anode and the average temperature of the cathode. Similarly, the two outputs are also defined to be the state variables of the model. The mathematical relationship of the different variables can be discovered by considering the mass balance of the control volumes for the anode and cathode side. Afterwards, the energy balance model can be derived and rearranged in terms of enthalpy, in order to discover the resulting differentiation of temperature as a result of the input and state variables. The open-loop block diagram represented in Figure 3 helps illustrate how the S-function would be beneficial to the model.

Generally, a PI controller increases accuracy by avoiding large disturbances and noise in the response, but this type of controller cannot increase the speed in the response. If a faster response is required in the system, the addition of the derivative (D) control to design a PID controller would be improved compared to the PI controller. Therefore, in this work, a PI controller was sufficient to add to the control system for the thermal aspect of the PEMFC as shown in Figure 4.

The deviation state variables are considered when implementing the PI controller. The PID controller input is the error where it is equal to the difference between the setpoint and the actual temperature of the fuel cell stack. Figure 4 shows the block diagram for the PEMFC system with feedback PID controller for temperature control and Figure 5 shows the detailed view of the PEMFC system with PID controller in a Simulink environment.

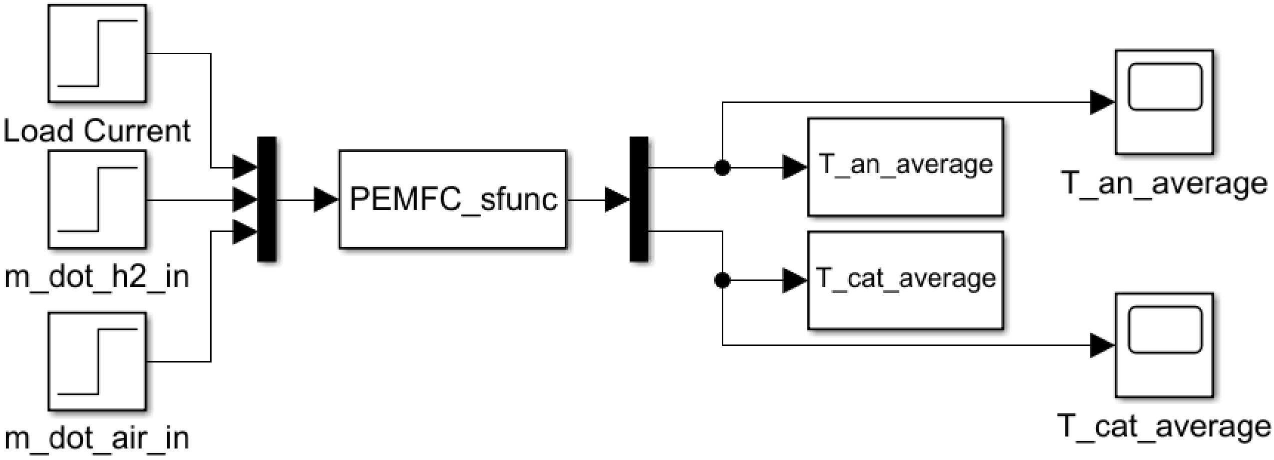


Figure 3. Open-Loop Block Diagram of the PEMFC as a S-function with 3 inputs and 2 output temperatures

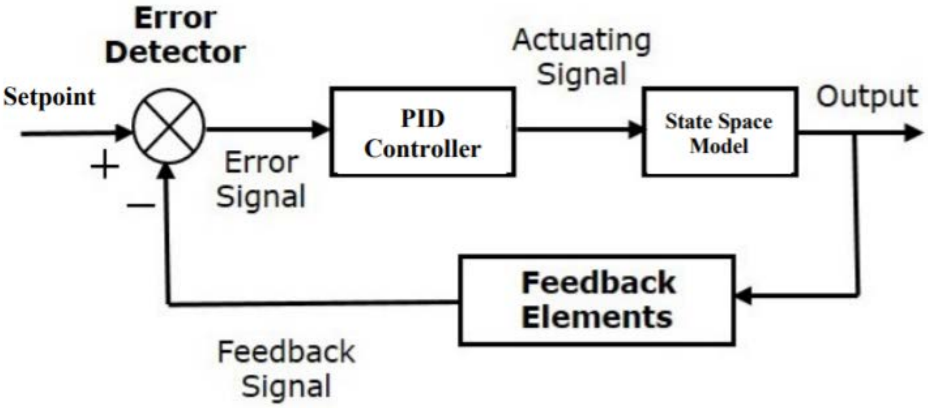


Figure 4. Block Diagram of PEMFC system with feedback PID Controller[7]

In the PI thermal model implemented in the Simulink, the PI controller could get good results when tuning the controller to 1×10^{-6} for Proportional (P) and 2.76×10^{-5} for Integral (I). The tuning method used here is the PID Controller Tuner in Simulink. It is a fast, convenient way to tune the controller by finding the closest gain values. Figure 6 shows the Simulink Controller Tuner, step plot: Reference tracking. From this window, the PI controller was tuned by modifying the response time and the transient behavior thus the mentioned gains were used.

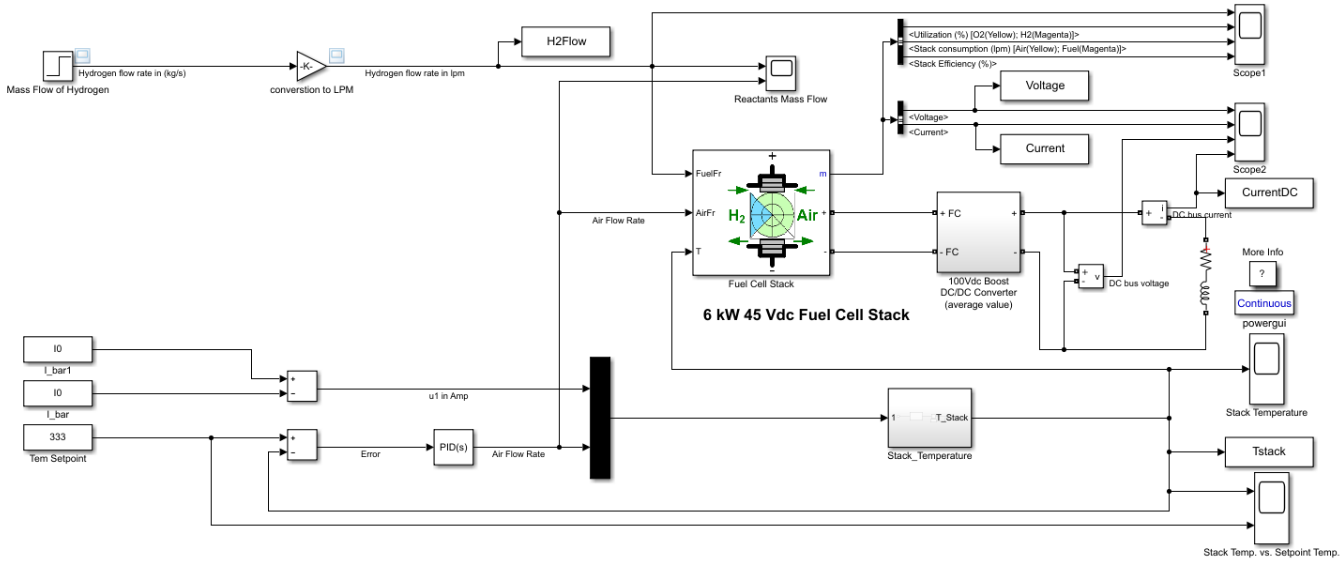
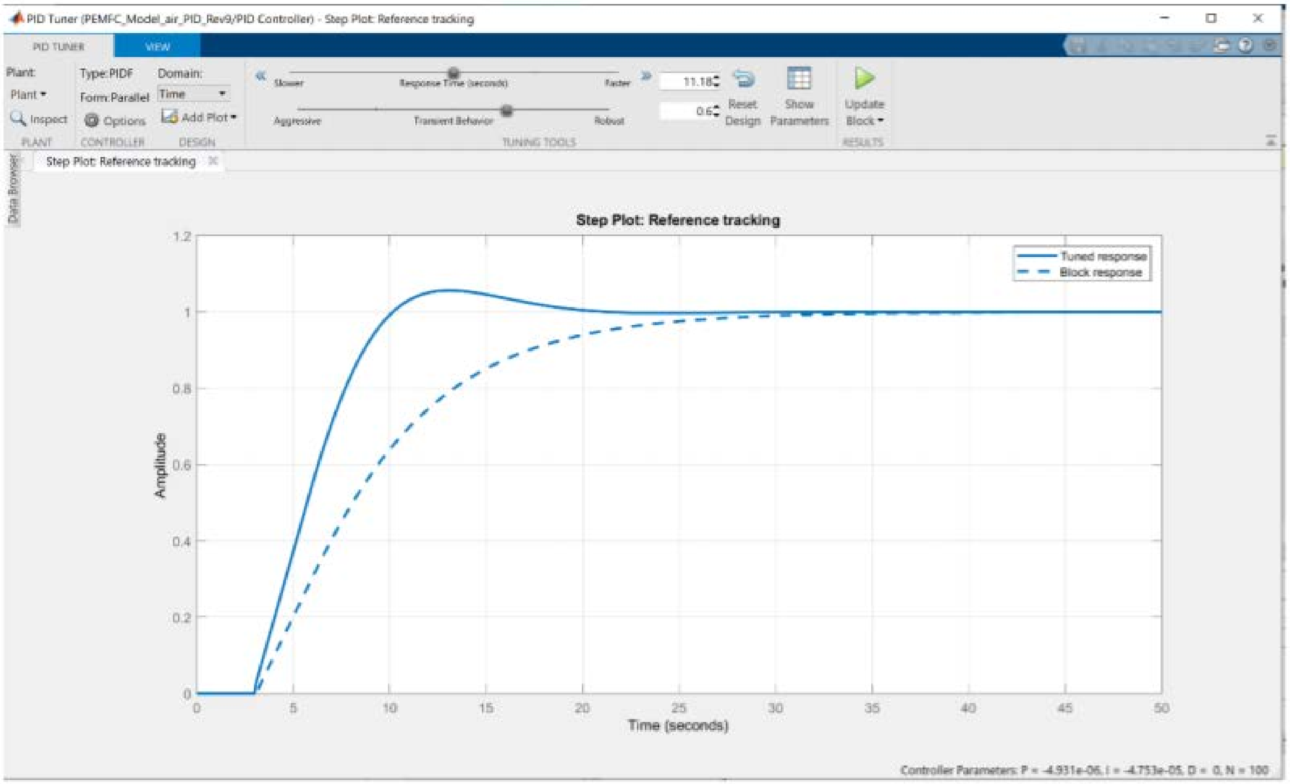


Figure 5. PID controller is added for temperature control of the PEMFC system in Simulink.



Controller Parameters: P = -4.931e-06, I = -4.753e-05, D = 0, N = 100

Figure 6. PID Controller Tuner in Simulink for temperature control

The principle objective in a feedback controller system is the setpoint tracking and a disturbance rejection. Generally, a controller can manage one change at a time. When the setpoint is changing and no disturbance is applied, the controller is tuned to accommodate this change of the setpoint, the system can control and try to maintain that setpoint. Nevertheless, if the setpoint is fixed (no changes apply) and the disturbance exists, then the controller will be tuned to react to the change of this disturbance. However, when both (the setpoint and the disturbance) are changing, the controller cannot accommodate this change, unless a specific tune is generated. This is a very difficult and complex task to achieve and when the controller can get this tuning to accommodate for both changes, then the controller will follow the setpoint and reject any disturbance on the system. This process can be tedious using trial-and-error method but can be an important learning experience for the students to appreciate the application of the concepts learned given the current state of technology, and to critically analyze and evaluate a system to thus build on their knowledge and skills.

Results

The controllers are tested and evaluated for two temperature setpoints: 323.15 K (50^{o}C) and 353.15 K (80^{o}C). The nominal operating temperature of the PEMFC stack, which is assumed to be average of the anode and cathode output temperatures, is that of 338.15 K (65^{o}C) The responses of the PI controller based system for the PEMFC temperature over time for step up and down of the setpoint temperature were observed to be reliable and consistent. The obtained results were very encouraging, as the PI controller settled to the setpoint temperature within a time of 20 seconds, which is less than that of open-loop temperature response and illustrated in Figures 7 and 8. For the implementation of the interface, the students will access to these example runs and results including Figures 7 and 8 to determine whether the system is responding as expected with its relation to the nominal operating temperature.

Table 1. Temperature results of the PI controller based system for two different setpoint step changes

Run No.	Initial Setpoint Temperature (K)	Steady State Air Flow Rate (SLPM)	Output Temperature (K)
1	323.15	504.6	323.2
2	353.15	504.6	353.1

Conclusion and Future Works

The growing interest in electrochemical systems within undergraduate students could be satisfied with the implementation of a dynamic model for a PEMFC. By utilizing an interface, students would be able to correlate the output response of a system according to its adjusted input. Similarly, these students would understand control systems and would be able to take a deeper look into the control strategies and modeling used for the PEMFC. With the implementation of this system in a simulated laboratory-based environment, students could benefit from valuable in-person experience that would not otherwise be achievable. This interface would therefore not only expand the knowledge and skills of students, but also introduce them to an emerging technology. Future work could be conducted to improve on the model and control interface by adjusting for different variables for inputs and outputs.

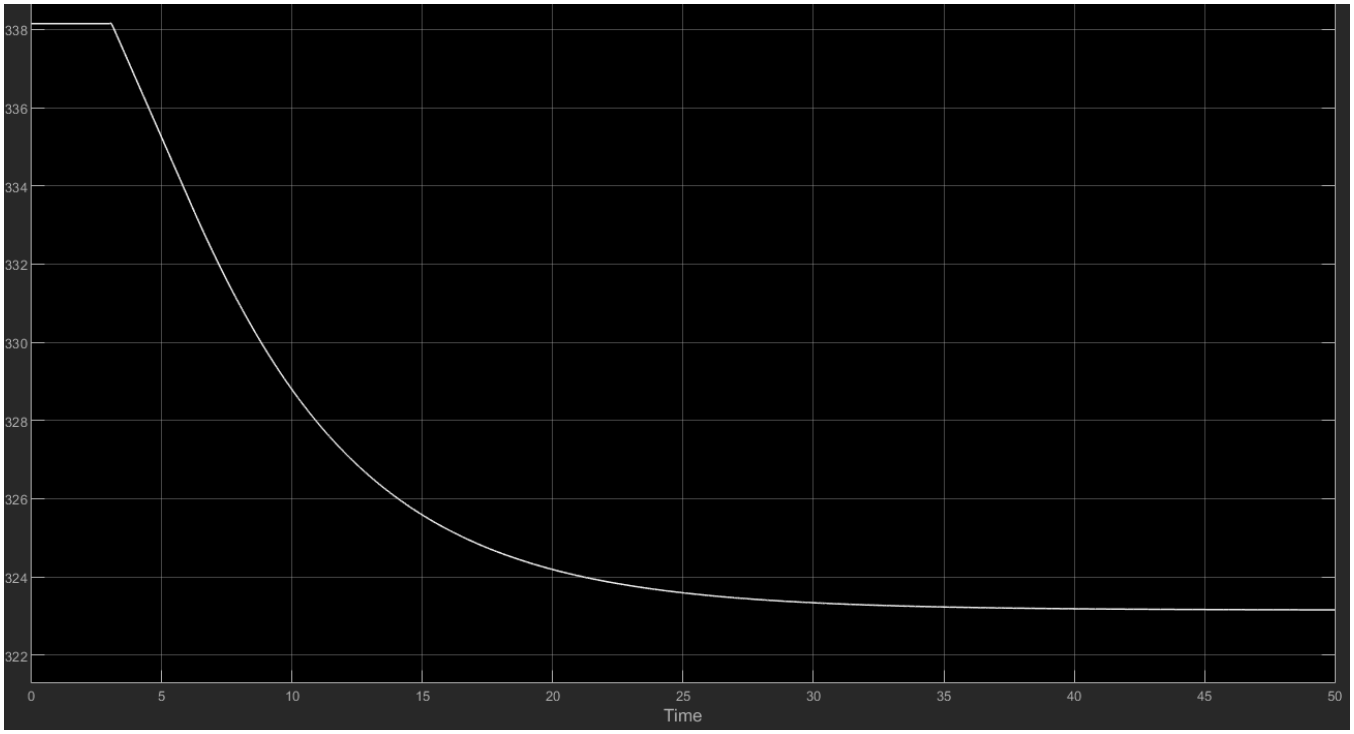


Figure 7. Stack temperature response for a step down of the setpoint temperature from 338.15K to 323.15K

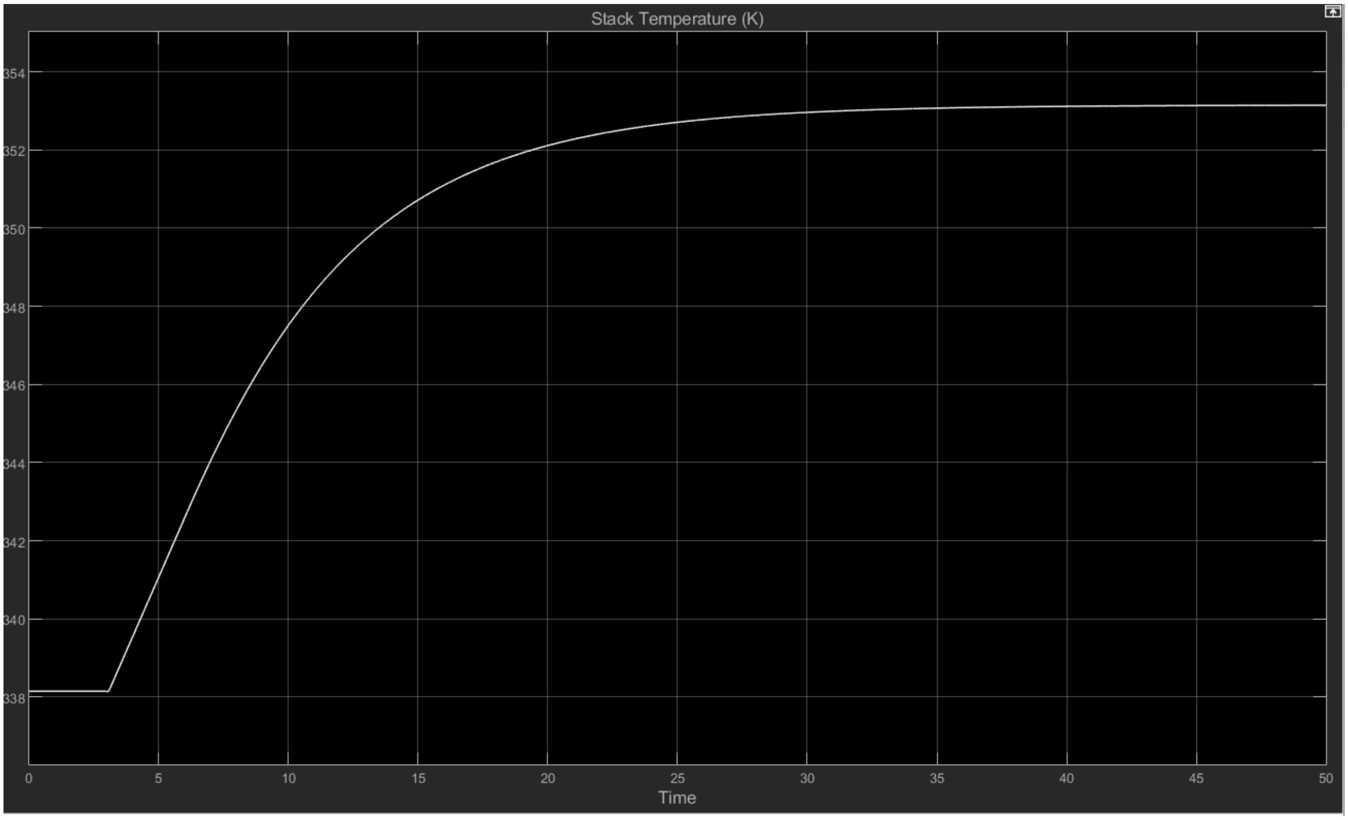


Figure 8. Temperature response of system for a step up from 338.15K to 353.15K

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