Quanser NI-ELVIS Trainer (QNET) Series:

QNET Experiment #05: HVAC System Identification

Heating, Ventilation, and Air Conditioning Trainer (HVACT)

Student Manual

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1. Laboratory Objectives

The objective of this experiment is to run open-loop tests on a Heating, Ventilation, and Air Conditioning (HVAC) plant in order to gain insights in the effects of heat radiation. The system dynamics are studied by collecting measurements that are used to perform system identification. The obtained model is required to design closed-loop controllers in subsequent experiments.

2. References

[1] *NI-ELVIS User Manual.*
[2] *QNET-HVACT User Manual.*

3. HVAC Plant Presentation

3.1. Component Nomenclature

As a quick nomenclature, Table 1, below, provides a list of the principal elements composing the Heating, Ventilation, and Air Conditioning (HVAC) Trainer system. Every element is located and identified, through a unique identification (ID) number, on the HVAC plant represented in Figure 1, below.

ID #	*Description*	*ID #*	*Description*
1	Heater / Halogen Lamp	**2**	Blower / Fan
3	Temperature Sensor	**4**	Chamber / Duct

Table 1 HVAC Component Nomenclature

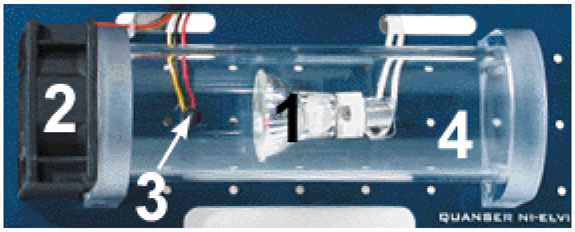


Figure 1 HVAC System

3.2. HVAC Plant Description

The QNET-HVAC Trainer system consists of a pexiglass duct, or chamber, equipped with a heater on one end and a blower on the other. A thermistor is placed in between at the location in the chamber where the temperature is to be controlled. The heater is made of a 12-Volt halogen lamp. The blower is a 24-Volt variable-speed fan.

4. Pre-Lab Assignments

This section must be read, understood, and performed before you go to the laboratory session.

4.1. Pre-Lab Assignment #1: Open-Loop Modelling

The HVAC plant consists of two inputs, namely the heater and blower voltages, for one output, the chamber temperature.

The system thermal resistance and capacitance are not known. Additionally, the heater and blower heatflow rate constants are also unknown. Therefore, system identification is required to model the dynamics of the plant.

The thermodynamics theory shows that the behaviour of space heating can be approximated by the following first-order transfer function, $G_h(s)$, from heater voltage to chamber temperature difference:

$$G_h(s) = \left(\frac{\Delta T_c(s)}{V_h(s)} = \frac{K_{ss\_h}}{\tau_h s + 1} \right) \quad [1]$$

where the difference with a constant ambient temperature is defined as:

$$\Delta T_c = T_c - T_a \quad [2]$$

Likewise, it can also be shown that the chamber cooling dynamics due to air blowing can be approximated by the following simple-lag Laplace transfer function, $G_b(s)$, from blower voltage to chamber temperature difference:

$$G_b(s) = \left(\frac{\Delta T_c(s)}{V_b(s)} = -\frac{K_{ss\_b}}{\tau_b s + 1} \right) \quad [3]$$

The HVAC model parameters and variables are defined in Table 2, below.

Symbol	*Description*	*Unit*
T_a	Ambient Temperature (Outside the Chamber)	ºC
T_c	Chamber Air Temperature	ºC
ΔT_c	Chamber Temperature Difference	ºC
V_h	Heater Input Voltage	V

Symbol	***Description***	***Unit***
V_b	Blower Input Voltage	V
K_{ss_h}	Heater Open-Loop Steady-State Gain	ºC/V
τ_h	Heater Open-Loop Time Constant	s
K_{ss_b}	Blower Open-Loop Steady-State Gain	ºC/V
τ_b	Blower Open-Loop Time Constant	s
s	Laplace Operator	rad/s
t	Continuous Time	s

Table 2 HVAC Model Nomenclature

4.2. Pre-Lab Assignment #2: Estimating The Heater Gain And Time Constant

As defined in Equation [1], the HVAC system steady-state gain and time constant during heating, i.e. K_{ss_h} and τ_h, can be determined experimentally by analyzing the system open-loop response to a step input. A typical first-order temperature response to a heater voltage step input is illustrated in Figure 2, below. The blower voltage is held constant at zero.

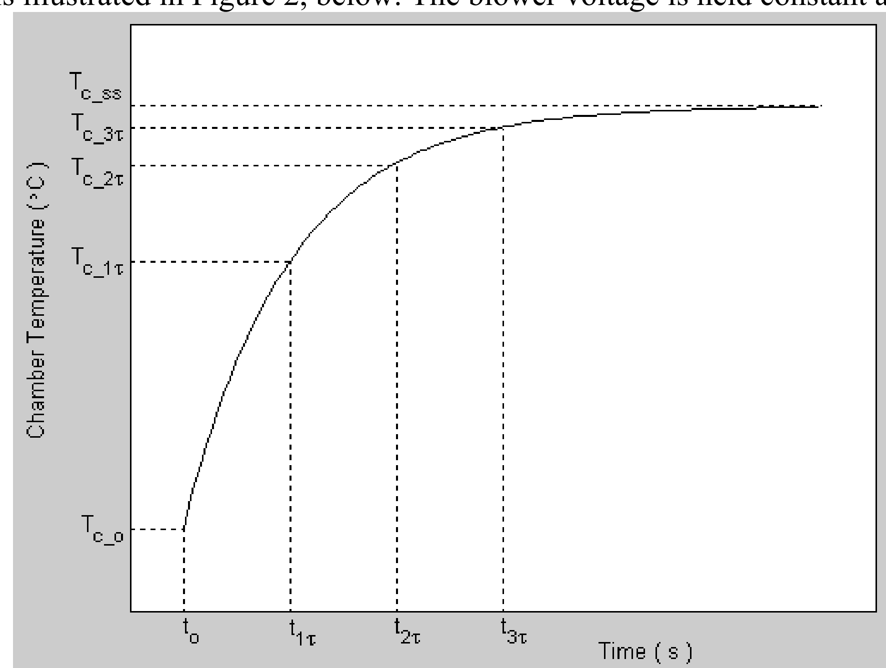


Figure 2 Model Parameter Estimation From A First-Order Step Response During Heating

During the laboratory session you will obtain the system responses to different amplitudes, K_{v_h}, of step input voltage to the heater. For each experimental step response, the following parameters, as shown in Table 3 and illustrated in Figure 2, should be measured:

Symbol	***Description***	***Unit***
t_0	Step Starting Time	s
T_{c_0}	Starting Chamber Temperature	ºC
T_{c_ss}	Steady-State Chamber Temperature	ºC

Table 3 First-Order Step Response Parameters

The time parameters presented in Figure 2, above, are characterized below such that $t_{1\tau}$ is defined by:

$$t_{\tau} = t_0 + \tau_h \qquad [4]$$

$t_{2\tau}$ by:

$$t_{2\,\tau} = t_0 + 2\,\tau_h \qquad [5]$$

and $t_{3\tau}$ by:

$$t_{3\,\tau} = t_0 + 3\,\tau_h \qquad [6]$$

1. Applying the theory associated with first-order systems, determine the chamber temperatures $T_{c\_1\tau}$, $T_{c\_2\tau}$, and $T_{c\_3\tau}$, obtained at the times, $t_{1\tau}$, $t_{2\tau}$, and $t_{3\tau}$, respectively. This is illustrated in Figure 2, above. The expressions obtained for $T_{c\_1\tau}$, $T_{c\_2\tau}$, and $T_{c\_3\tau}$ should be functions of T_{c_0} and T_{c_ss}.

2. As illustrated in Figure 2, above, the measurement times $t_{1\tau}$, $t_{2\tau}$, and $t_{3\tau}$ can be estimated by locating $T_{c\_1\tau}$, $T_{c\_2\tau}$, and $T_{c\_3\tau}$, respectively, on the experimentally-obtained step response plot and by measuring their corresponding time values. As induced by Equations [4], [5], and [6], each measurement time results in an estimate of the heater open-loop time constant τ_h. Express the resulting time constant estimates, namely τ_{h1}, τ_{h2}, and τ_{h3}, as functions of t_0 and the measurement times $t_{1\tau}$, $t_{2\tau}$, and $t_{3\tau}$, respectively.

3. A valid estimation of the heater time constant τ_h is assumed to be the average of the three

previously-obtained estimates τ_{h1}, τ_{h2}, and τ_{h3}. Determine the expression for τ_h as a function of τ_{h1}, τ_{h2}, and τ_{h3}.

4. Finally determine the expression for K_{ss_h} as a function of K_{v_h}, T_{c_0}, and T_{c_ss}.

4.3. Pre-Lab Assignment #3: Estimating The Blower Gain And Time Constant

As defined in Equation [3], the HVAC system steady-state gain and time constant during blowing, i.e. K_{ss_b} and τ_b, can also be determined experimentally by analyzing the system open-loop response to a step input. A typical first-order temperature response to a blower voltage step input is illustrated in Figure 3, below. The heater voltage is held constant at zero.

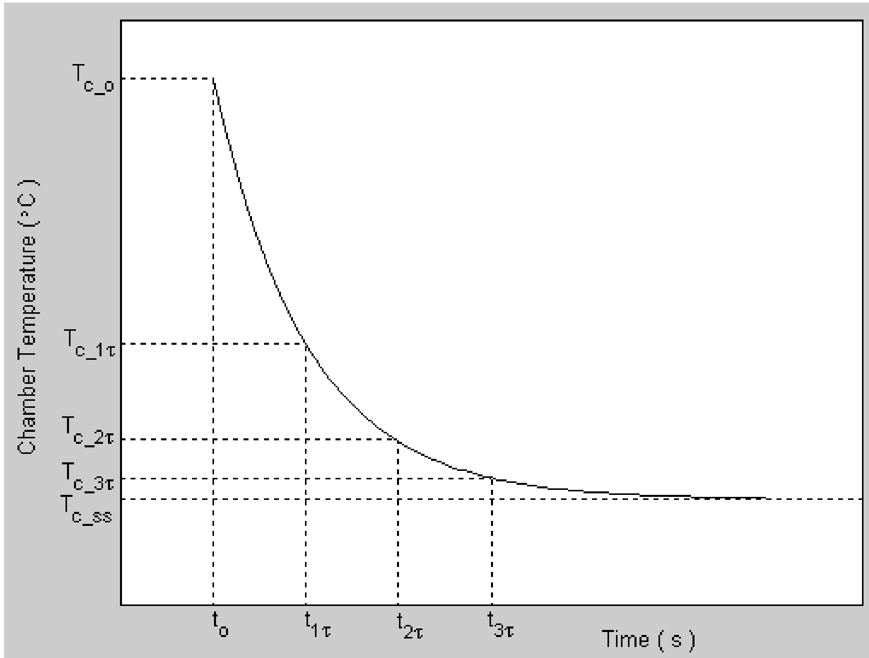


Figure 3 Model Parameter Estimation From A First-Order Step Response During Blowing

During the laboratory session you will obtain the system responses to different amplitudes, K_{v_b}, of step input voltage to the blower. For each experimental step response, the same parameters as those shown in Table 3 and illustrated in Figure 3, should be measured.

However in this case, the time parameters presented in Figure 3, above, are characterized below such that $t_{1\tau}$ is defined by:

$$t_{\tau} = t_0 + \tau_b \quad [7]$$

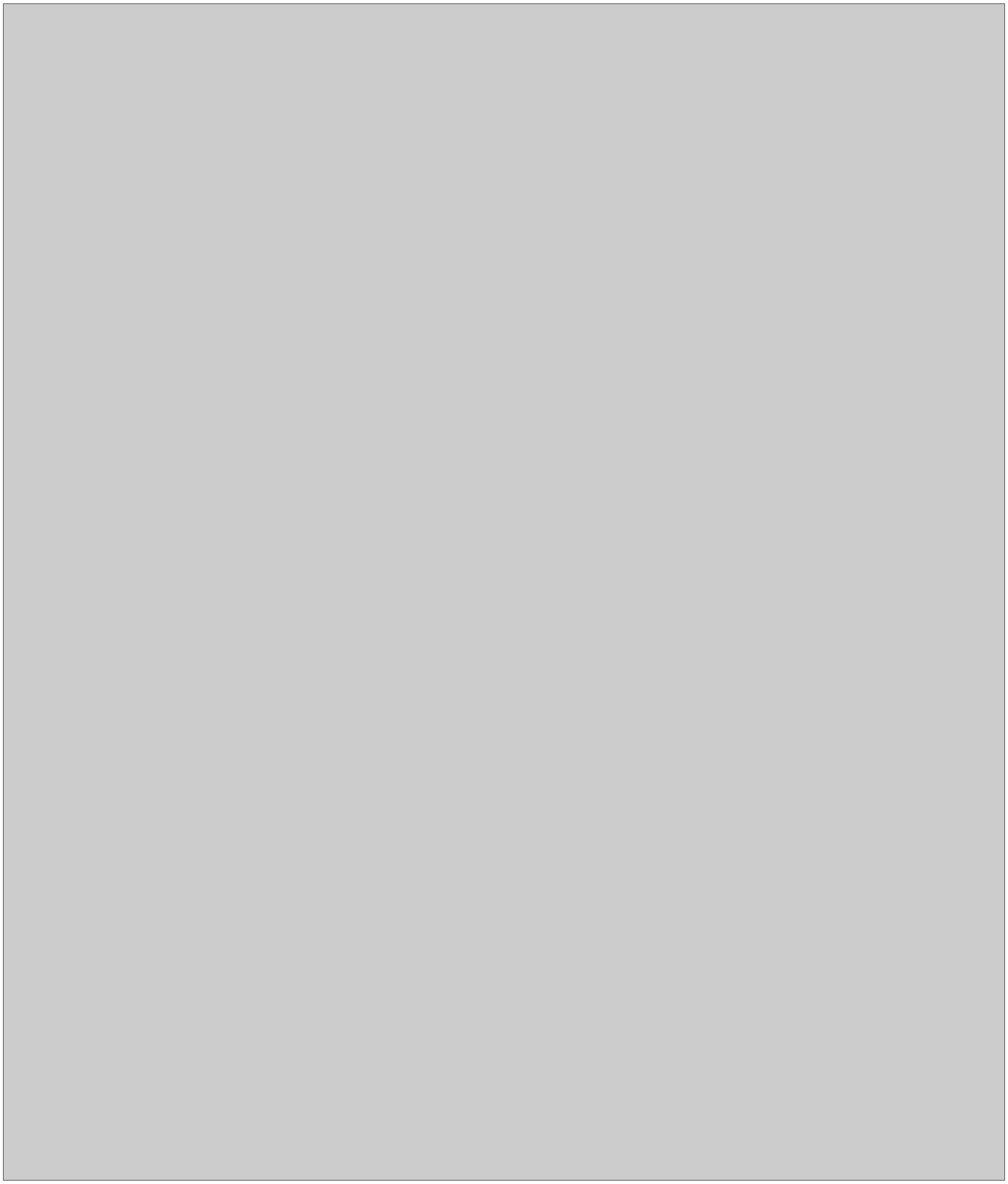
$t_{2\tau}$ by:

$$t_{2\,\tau} = t_0 + 2\,\tau_b \quad [8]$$

and $t_{3\tau}$ by:

$$t_{3\,\tau} = t_0 + 3\,\tau_b \quad [9]$$

1. Following a reasoning similar to the one previously detailed in Pre-Lab Assignment #2, derive a way to estimate the blower open-loop time constant τ_b.
   Hint:
   τ_b should result as the average of three different experimental estimates τ_{b1}, τ_{b2}, and τ_{b3}, which will be expressed as a functions of t_0 and $t_{1\tau}$, $t_{2\tau}$, and $t_{3\tau}$, respectively.



2. Finally derive an expression for K_{ss_b} as a function of K_{v_b}, T_{c_0}, and T_{c_ss}.

5. In-Lab Session

5.1. System Hardware Configuration

This in-lab session is performed using the NI-ELVIS system equipped with a QNET-HVACT board and the Quanser Virtual Instrument (VI) controller file *QNET_HVAC_Lab_05_Sys_ID.vi*. Please refer to Reference [2] for the setup and wiring information required to carry out the present control laboratory. Reference [2] also provides the specifications and a description of the main components composing your system.

Before beginning the lab session, ensure the system is configured as follows:

QNET HVACT module is connected to the ELVIS.
ELVIS Communication Switch is set to BYPASS.
DC power supply is connected to the QNET HVAC Trainer module.
The 4 LEDs +B, +15V, -15V, +5V on the QNET module should be ON.

5.2. Software User-Interface

Please follow the steps described below:

Step 1. Read through Section 5.1 and go through the setup guide in Reference [2].

Step 2. Open the VI controller *QNET_HVAC_Lab_05_Sys_ID.vi* shown in Figure 4. The default sampling rate for the implemented digital controller is 350 Hz. However, you can adjust it to your system's computing power. Please refer to Reference [1] for a complete system's description. The chamber temperature, directly sensed by the thermistor, is plotted on a chart as well as displayed in a Numeric Indicator and a Thermometer located in the *Temperature (degC)* front panel box. The values are in degrees Celsius. Run the LabVIEW VI (Ctrl+R) to initialize the open-loop controller. At this point both heater and blower voltages (i.e. V_h and V_b) are set to zero and the chamber temperature is read. The vertical toggle switch in the *Input Signal Properties* box allows you to choose between the heating or cooling process of the system. In heating mode, the blower voltage (V_b) is zero and the heater voltage (V_h) can be set by the user through the *Vh* Numeric Control. Likewise in cooling mode, the heater voltage is set to zero while the blower voltage is user-defined through the *Vb* Numeric Control. However, the green START push button should be pressed in order for both commanded voltages to be applied to the HVAC plant. With the open-loop control action active, the initially green START push button should now show as a red STOP button that you can trigger to pause the controller execution.

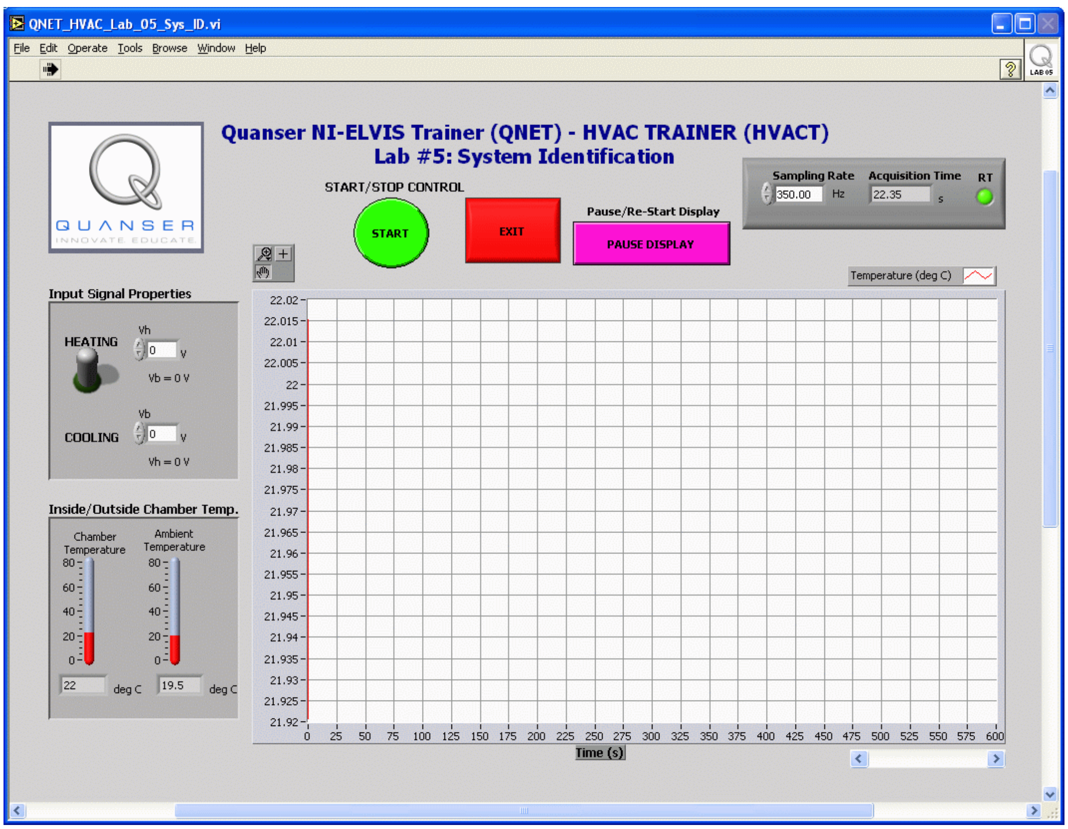


Figure 4 Front Panel Used for the QNET-HVACT System Identification Laboratory

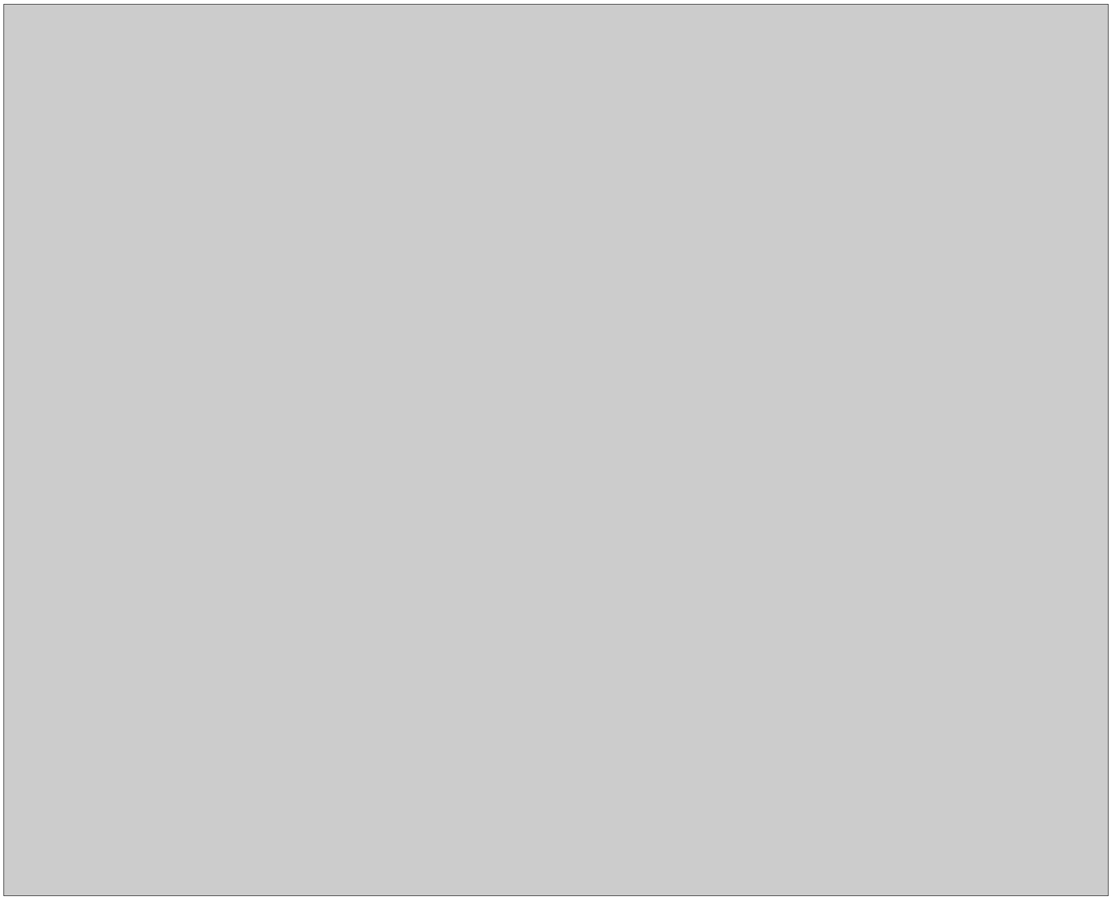
5.3. Estimate The Heater Steady-State Gain And Time Constant

Step 3. First, select *COOLING* in the *Input Signal Properties* box by flipping as required the vertical toggle switch. Ensure that the *Vb* Numeric Control is set to more than 16 Volts and that the initially green START push button has been pressed. The fan should now blow in order to initialize the system by bringing the chamber to ambient temperature.

Step 4. Click on the red STOP button to stop the blowing once a steady-state temperature has been reached. Let the chamber air settle for about 20 seconds and reach ambient temperature.

Step 5. Then, select *HEATING* in the *Input Signal Properties* box by flipping the toggle switch. Set the *Vh* Numeric Control to 1.5 Volts. Clear the chart by right clicking on it and selecting the *Clear Chart* context menu item. You can now start the step input test by pressing the green START push button, which will apply the desired voltages to the system. The halogen lamp should now be heating proportionally to V_h and the chamber temperature should be rising. The settling time should be less than 600 seconds, so that the complete step response fits within the chart time scale. At this point, also stop the heater by pressing the red STOP button. DO NOT press EXIT and do not stop the VI.

Step 6. Make a screen capture of the obtained step response plot once the response has reached steady-state and join a printout to your report. Your actual response should look similar to the theoretical temperature heating plot presented in Figure 2.



Step 7. Determine the characteristics of the obtained step response plot by using the Graph Palette located on top of the Chart top left corner. Fill up the following table (i.e. Table 4) by measuring the required data points from the actual plot and by carrying out the estimation procedure detailed in Pre-Lab Assignment #2. In Table 4, the first line presents the data from *Step #1*, which corresponds to a heater input voltage of 1.5 Volts (i.e. K_{v_h}). The second line of Table 4 is for an input step of 3.0 Volts, which is called *Step #2*. Determine the corresponding estimates for the heater steady-state gain, K_{ss_h}, and time constant, τ_h.

Step #	K_{v_h} [V]	t_0 [s]	T_{c_0} [ºC]	T_{c_ss} [ºC]	$T_{c\_1\tau}$ [ºC]
1	1.5				
2	3				

Step #	$T_{c\_2\tau}$ [ºC]	$T_{c\_3\tau}$ [ºC]	$t_{1\tau}$ [s]	$t_{2\tau}$ [s]	$t_{3\tau}$ [s]
1					
2					

Step #	τ_{h1} [s]	τ_{h2} [s]	τ_{h3} [s]	τ_h [s]	K_{ss_h} [ºC/V]
1					
2					
	Average Values:				

Table 4 Heating Step Actual Response Characteristics And Parameter Estimation

Step 8. Obtain a second step response (*Step #2*) for the heating process by repeating Steps 2 to 6, as described above, but with the *Vh* Numeric Control set to 3.0 Volts instead of 6 in *Step #1*.

Step 9. From your experimental results from *Step #1* and *Step #2* in Table 4 above, take the average of the two estimates found for the heater steady-state gain, K_{ss_h}, and time constant, τ_h. What are your final estimated (i.e. average) values for K_{ss_h} and τ_h?

Step 10. Once your results are obtained, you can stop the VI by pressing the red EXIT button.

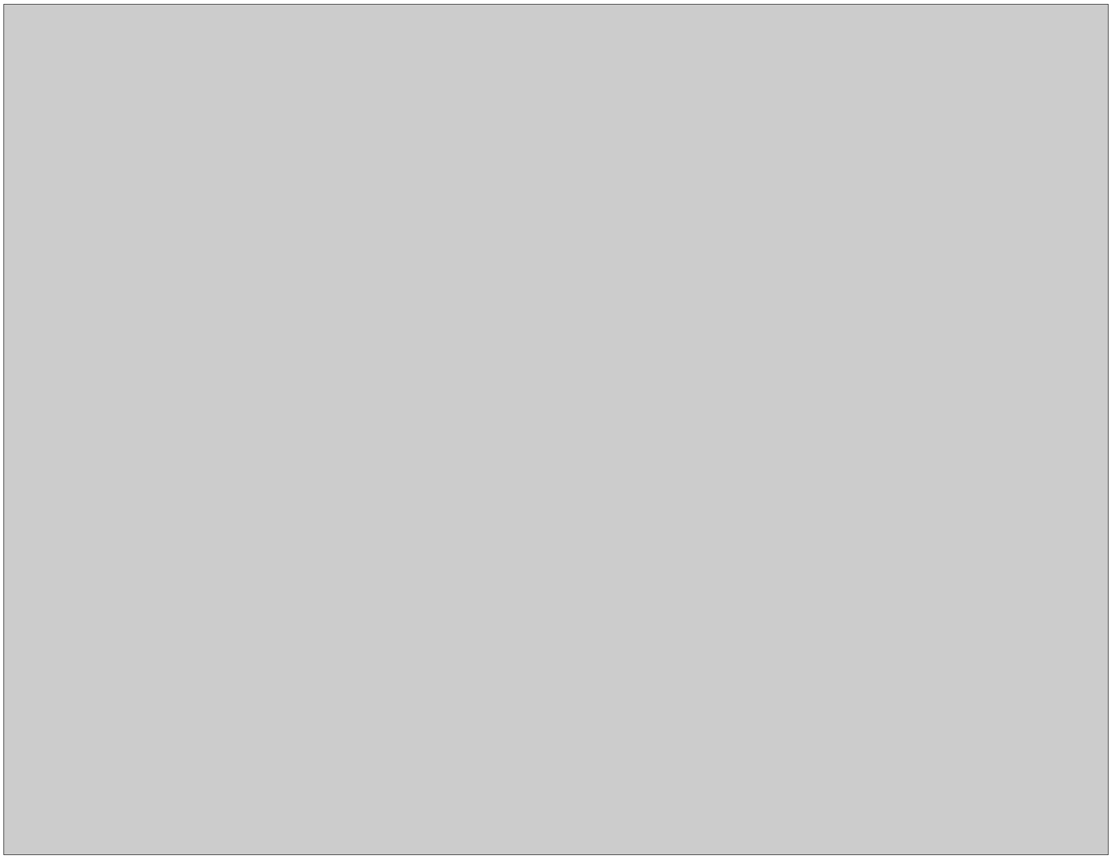
5.4. Estimate The Blower Steady-State Gain And Time Constant

Step 11. Select *HEATING* in the *Input Signal Properties* box by flipping as required the vertical toggle switch. Set the *Vh* Numeric Control to 4.0 Volts. Start the LabVIEW VI (Ctrl+R) if it has been stopped and ensure that the initially green START push button has been pressed. The halogen lamp should now be on and heat up the inside of the chamber. This raises the chamber temperature and initializes the system before the cooling step.

Step 12. Monitor the heating the chamber on the front panel. Be prepared to toggle the switch to *COOLING* once the chamber temperature is above 60 degrees Celsius. This will stop heating and start blowing/cooling step test. However beforehand, ensure that the *Vb* Numeric Control is first set to 14 Volts.

Step 13. Once the temperature is above 60 °C, first clear the chart by right clicking on it and selecting the *Clear Chart* context menu item. Then select *COOLING* in the *Input Signal Properties* box by flipping the toggle switch. The open-loop step input test is now started, by applying the desired voltages, V_b and V_h, to the system. The fan should now be blowing proportionally to V_b and the chamber temperature should be dropping. The settling time should be less than 600 seconds, so that the complete step response fits within the chart time scale. At this point, also stop the blower by pressing the red STOP button. DO NOT press EXIT and do not stop the VI.

Step 14. Make a screen capture of the obtained step response plot once the response has reached steady-state, which should be around ambient temperature, and join a printout to your report. Your actual response should look similar to the theoretical temperature cooling plot presented in Figure 3.



Step 15. Determine the characteristics of the obtained step response plot by using the *Graph Palette* located on top of the Chart top left corner. Fill up the following table (i.e. Table 5) by measuring the required data points from the actual plot and by carrying out the estimation procedure detailed in Pre-Lab Assignment #3. In Table 5, the first line presents the data from *Step #1*, which corresponds to a blower input voltage of 14 Volts (i.e. K_{v_b}). The second line of Table 5 is for an input step of 18 Volts, which is called *Step #2*. Determine the corresponding estimates for the blower steady-state gain, K_{ss_b}, and time constant, τ_b.

Step #	K_{v_b} [V]	t_0 [s]	T_{c_0} [ºC]	T_{c_ss} [ºC]	$T_{c\_1\tau}$ [ºC]
1	14				
2	18				

Step #	$T_{c\_2\tau}$ [ºC]	$T_{c\_3\tau}$ [ºC]	$t_{1\tau}$ [s]	$t_{2\tau}$ [s]	$t_{3\tau}$ [s]
1					
2					

Step #	τ_{b1} [s]	τ_{b2} [s]	τ_{b3} [s]	τ_b [s]	K_{ss_b} [ºC/V]
1					
2					
	Average Values:				

Table 5 Blowing Step Actual Response Characteristics And Parameter Estimation

Step 16. Obtain a second step response (*Step #2*) for the blowing process by repeating Steps 10 to 14, as described above, but with the *Vb* Numeric Control set to 18 Volts instead of 6 in *Step #1*.

Step 17. From your experimental results from *Step #1* and *Step #2* in Table 5 above, take the average of the two estimates found for the blower steady-state gain, K_{ss_b}, and time constant, τ_b. What are your final estimated (i.e. average) values for K_{ss_b} and τ_b?

Step 18. Once your results are obtained, you can stop the VI by pressing the red EXIT button.

5.5. Estimate The Heater And Blower Deadband Voltages

Step 19. Let us define V_{h_off} and V_{b_off} the heater and blower positive (i.e. upper limit) deadband voltages, respectively. Deadband, or deadzone, is chiefly due to nonlinearity in the system such as static friction, or electrical offset, and the like.

Step 20. To determine V_{h_off} experimentally, select *HEATING* in the *Input Signal Properties* box by flipping as required the vertical toggle switch and set the *Vh* Numeric Control to 0 Volts to start. Start the LabVIEW VI (Ctrl+R) if it has been stopped and ensure that the initially green START push button has been pressed. Both halogen lamp and fan should be off as their respective input voltages, V_h and V_b, are set to zero. Now slowly increase V_h, by steps of 0.1 Volts, until the halogen lamp filament becomes on and turns orange. You can do so by using the increment/decrement button on the left side of the *Vh* Numeric Control. Wait for a few seconds between two increment steps to let the heater settle at the new input voltage. Stop incrementing as soon as the bulb starts switching on.

Step 21. What is your measured heater deadband voltage?

Step 22. To determine V_{b_off} experimentally, set the *Vb* Numeric Control in the *Input Signal Properties* box to 0 Volts and flip the toggle switch to *COOLING*. Start the LabVIEW VI (Ctrl+R) if it has been stopped and ensure that the initially green START push button has been pressed. Both halogen lamp and fan should be off as their respective input voltages, V_h and V_b, are set to zero. Now slowly increase V_b, by steps of 0.1 Volts, until the fan starts to turn. You can do so by using the increment/decrement button on the left side of the *Vb* Numeric Control. Wait for a few seconds between two increment steps to let the fan settle at the new input voltage. Stop incrementing as soon as the fan has started.

Step 23. What is your measured blower deadband voltage?

Step 24. Both V_{h_off} and V_{b_off} could be used in a control system scheme for deadband compensation.

Step 25. Shut off the PROTOTYPING POWER BOARD switch and the SYSTEM POWER switch at the back of the ELVIS unit. Unplug the module AC cord. Finally, stop the VI by pressing the red EXIT button.

Step 26. Before leaving the laboratory session, ensure that you have all the experimental results required for your lab report