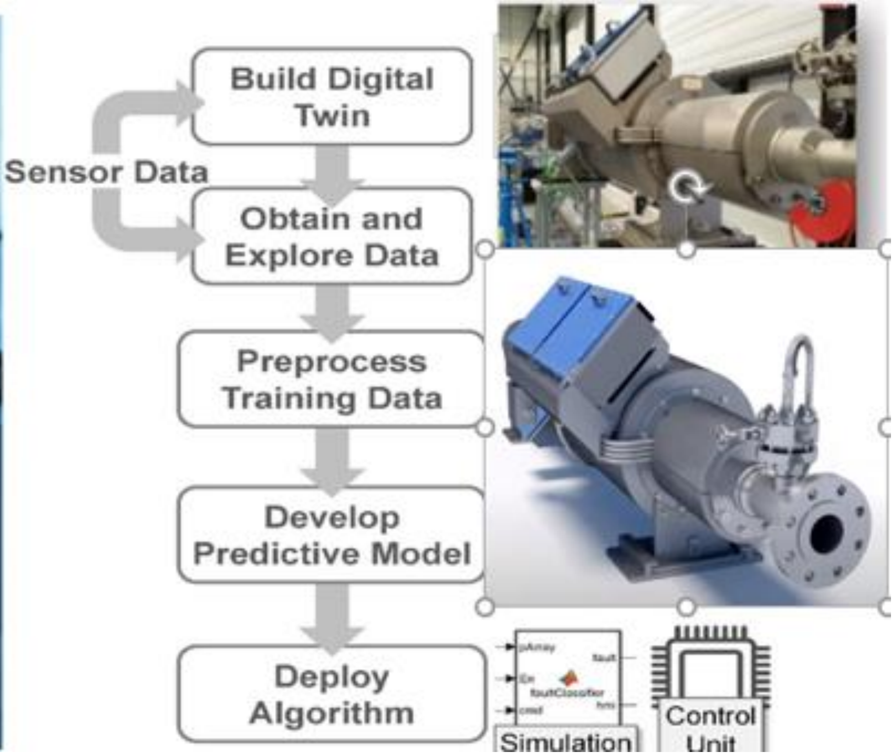
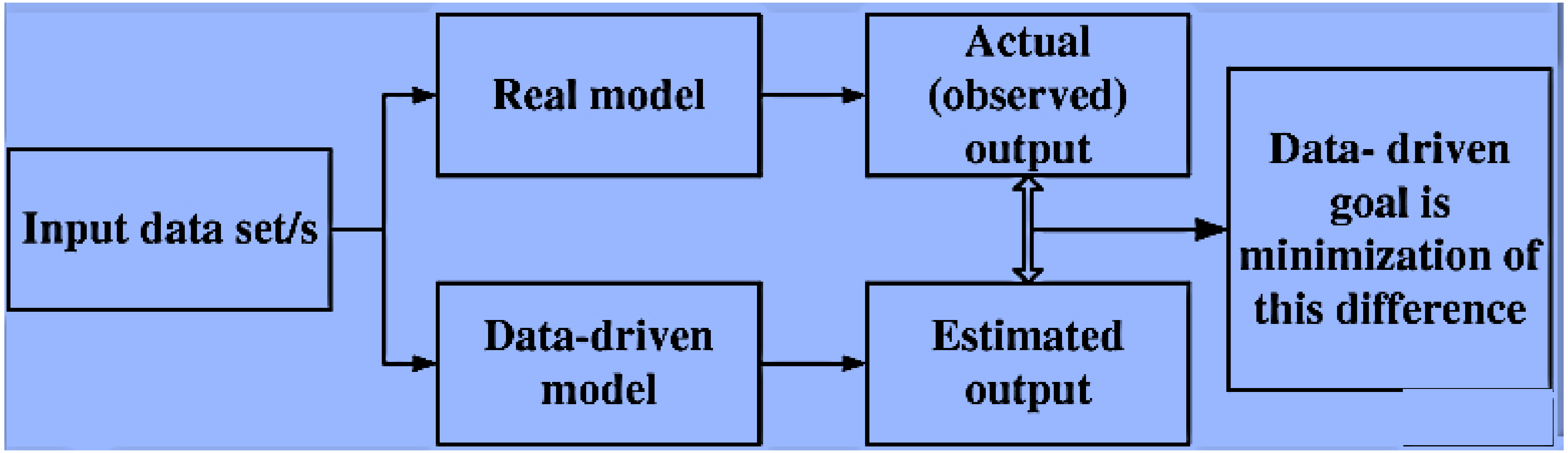


Data-Driven Modelling



	Intelligent Control System KOM 5101
1	Introduction to Intelligent Control Systems (knowledge-based vs data-driven systems)
2	Computational Thinking Tools
3	Dynamical Systems Modelling (Control System Toolbox could be used to transfer functions, state space models)
4	Model Predictive Control MPC (MPC Toolbox can be used)
5	Intro to Machine Learning (Stats & Machine Learning Toolbox could be used)
6	Data-driven Modeling -with machine learning (Stats & Machine Learning Toolbox could be used)
7	Data-driven Modeling -with system Identification (SysID toolbox could be used)
8	Midterm Exam
9	Data-driven Control Techniques -Extremum seeking (Simulink Control Design could be used)
10	Data-driven Control Techniques -Model reference adaptive control (Simulink Control Design could be used)
11	Intro to Deep Learning (Deep Learning Toolbox could be used)
12	Reinforcement Learning (RL Toolbox could be used)
13	Student's Projects
14	Student's Projects
15	Final Exam

MathWorks®

Dr. Julia Hoerner
Dr. Marco Rossi
Dr. Melda Ulusoy

Intelligent Control Systems KOM5101	Preparation + Homework	Matlab Drive
1 Introduction to intelligent control systems (knowledge-based vs data-driven systems)	Select the project from https://github.com/mathworks/MathWorks-Excellence-in-Innovation#mathworks-excellence-in-innovation-projects	https://drive.matlab.com/sharing/c1f9073b-a0b0-4966-95b0-c107691878da
2 Computational thinking tools	Work with the Virtual Hardware and Labs for Control. Solve the following Labs Lab4_PositionAnalysis.mlx Lab3_PositionControl.mlx Lab2_VehicleModel.mlx Lab1_CruiseControl.mlx	https://drive.matlab.com/sharing/77e65af2-6ffd-4709-a0bd-c36e0fbe50df
3 Dynamical systems modelling	1. Study and Obtain the state space model of a crane system. 2. Study and Obtain the state space model of the Lateral Vehicle Dynamics bicycle model with two degrees of freedom, lateral position and yaw angle.	https://drive.matlab.com/sharing/31e0ba39-b3f8-402c-a428-6a5b9d620081
4 Model Predictive Control MPC	Study and work with the MPC models explained. Use the MPC Toolbox of Matlab and the apmonitor server. Learn how to work with the drivingScenarioDesigner. Program the MPC algorithms using Simulink and Live scripts. Modify Models and MPC parameter and settings.	https://drive.matlab.com/sharing/398fa9fa-4650-4316-ab2b-0d228b24f48c
5 Machine Learning	 **Machine Learning Onramp** 6 modules | 2 hours | Languages Learn the basics of practical machine learning methods for classification problems.	

	Intelligent Control Systems KOM5101	Preparation + Homework	Matlab Drive
6	Data-Driven Modelling	Use the FOPDT example and do your own model estimation. Work with FOPDT live scripts **FOPDT_Lab/L06_Assignment_graphical** **Use the 2nd_order_linear model and obtain the regression parameters**	https://drive.matlab.com/sharing/71cc50d0-e79e-47e3-b91e-9ba1aa1cf78b

Evaluation System

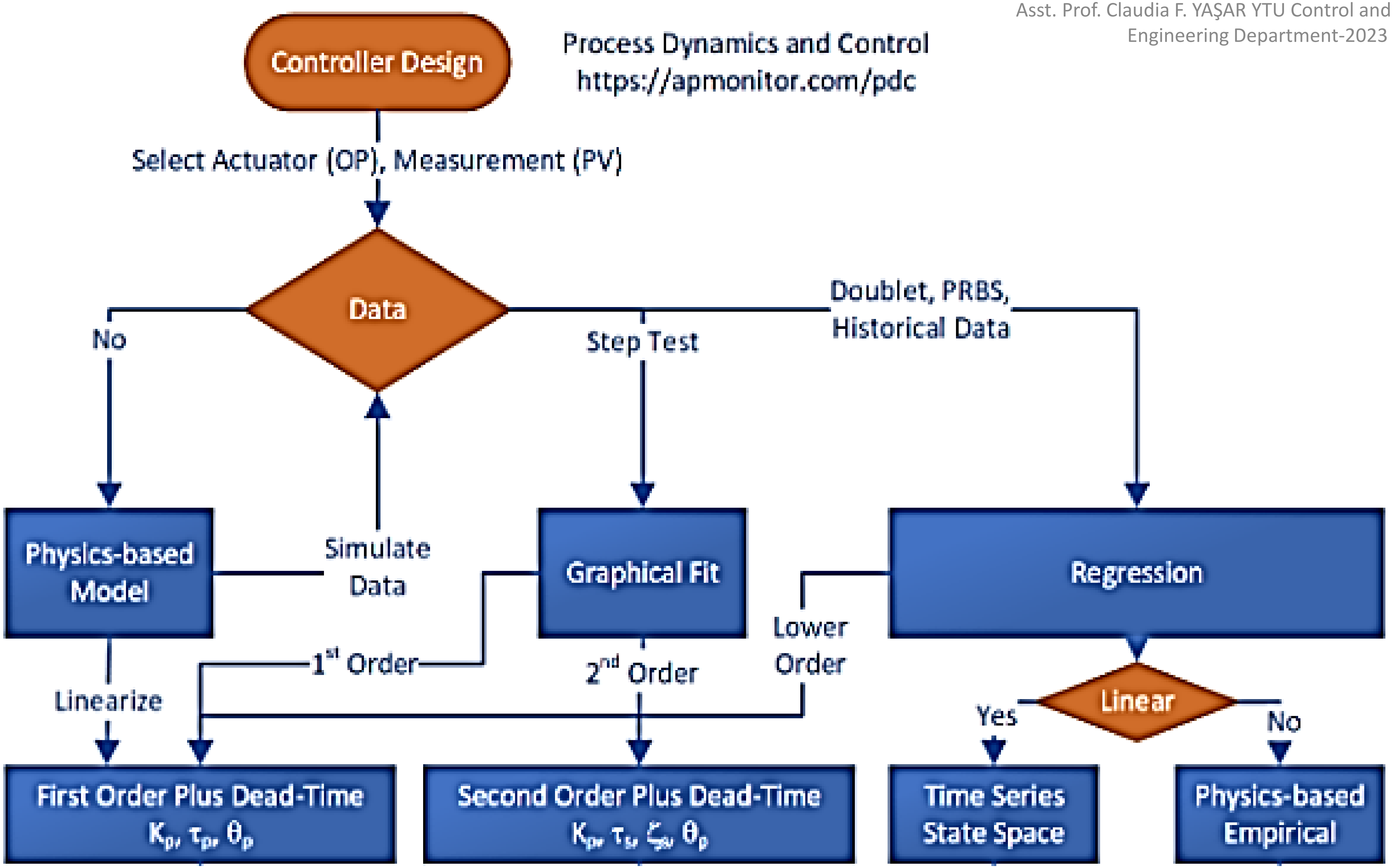
Homework Assignments	30%

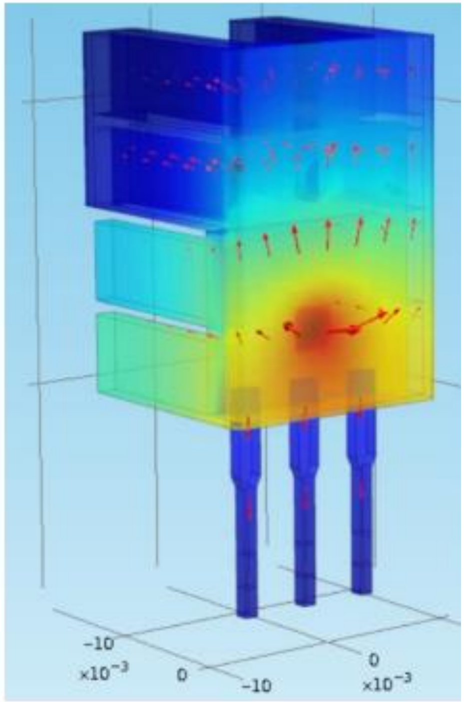
- Week 2 (start) – Week 8(deadline)
  - Control Design Onramp with Simulink (20min - Chapter 1,2,3)
- Week 4 (start) – Week 8 (deadline)
  - Control Design Onramp with Simulink (30min - Chapter 4,5,6,7)
- Week 5 (start) – Week 8 (deadline)
  - Machine Learning Onramp (2h)
- Week 8 (start) - Week 11 (deadline)

  Deep Learning Onramp (2h)

Week 9 (start) –Week 11 (deadline)

- Reinforcement Learning Onramp (3h)


Controller Design
Process Dynamics and Control
https://apmonitor.com/pdc
Select Actuator (OP), Measurement (PV)
Data
No
Step Test
Doublet, PRBS, Historical Data
Physics-based Model
Simulate Data
Graphical Fit
Regression
Linearize
1st Order
2nd Order
Lower Order
Linear
Yes
No
First Order Plus Dead-Time
K_p, τ_p, θ_p
Second Order Plus Dead-Time
K_p, τ_s, ζ_s, θ_p
Time Series State Space
Physics-based Empirical



Quantity
Initial temperature (T_0)
Ambient temperature (T_∞)
Heater output (Q)
Heater factor (α)
Heat capacity (C_p)
Surface Area (A)
Mass (m)
Overall Heat Transfer Coefficient (U)
Emissivity (ε)
Stefan Boltzmann Constant (σ)

$$m\, c_p \frac{dT}{dt} = \sum \dot{h}_{in} - \sum \dot{h}_{out} + Q$$

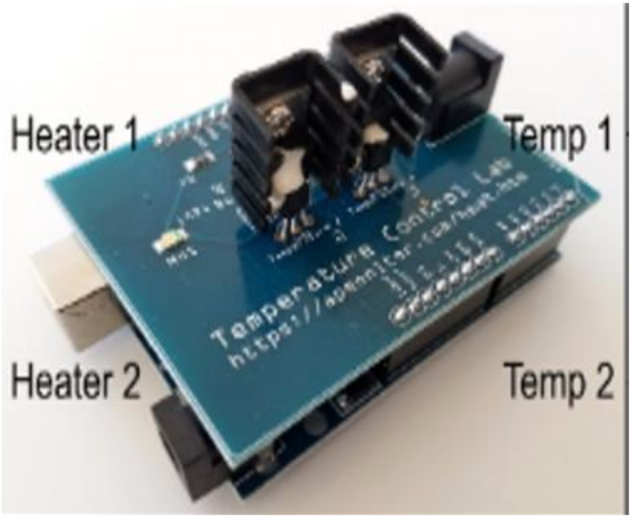
Q is the rate of heat transfer

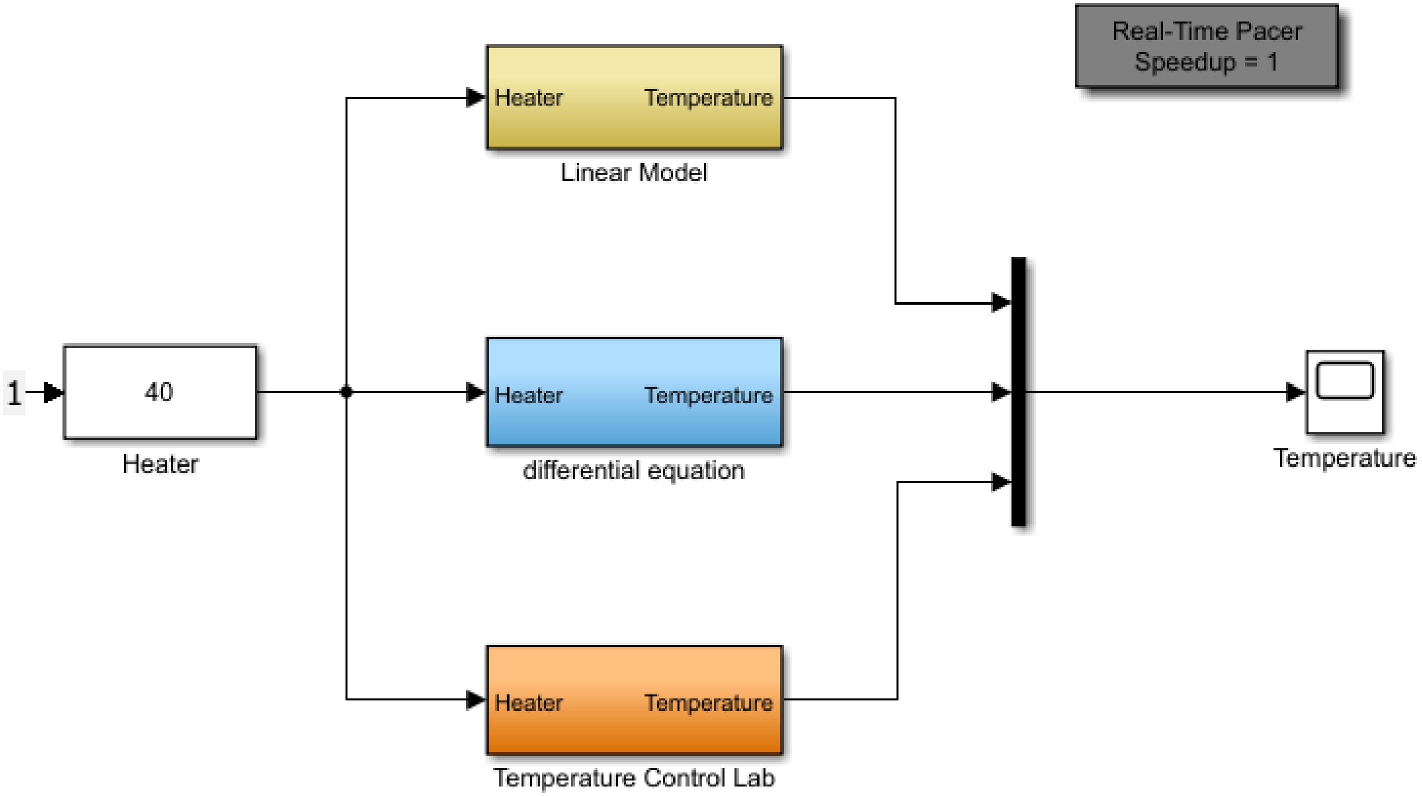
$$m\, c_p \frac{dT}{dt} = \underbrace{U\, A\, (T_\infty - T)}_{\textbf{Convection}} + \underbrace{\epsilon\, \sigma\, A\, \left(T_\infty^4 - T^4\right)}_{\textbf{Radiation}} + \underbrace{\alpha Q}_{\textbf{Heater}}$$

https://apmonitor.com/do/index.php/Main/AdvancedTemperatureControl

REAL TIME EXPERİMENTS - TC Lab – Dynamic model of a single heater

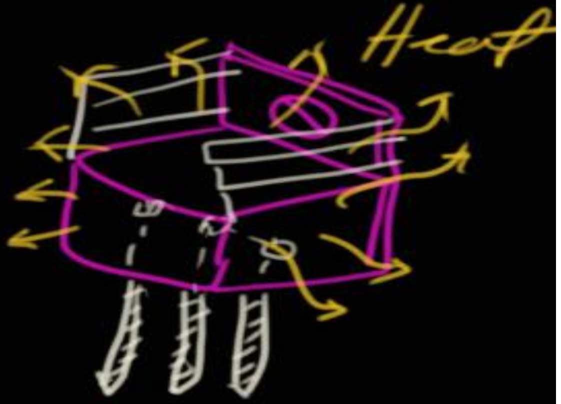
m = 0.001; % kg (1 gm)
% heat transfer coefficient
U = 200; % W/m^2-K
% surface area
A = 2 / 100^2; % m^2
% heat capacity
Cp = 4900.0; % J/kg-K





REAL TIME EXPERİMENTS - TC Lab – Dynamic model of a single heater

Total Energy Balance



$$mc_p\frac{dT}{dt} = \underbrace{UA(T_\infty - T)}_{\text{convection}} + \underbrace{\epsilon\sigma(T_\infty^4 - T^4)}_{\text{Radiation}} + \underbrace{\alpha Q}_{\text{heater}}$$

If we ignore Radiation components

$$* \; mc_p\frac{dT}{dt} = UA(T_\infty - T) + \alpha Q$$

First order differential equation

$$\overbrace{\frac{mc_p}{UA}}^{\tau_p}\frac{dT}{dt} + T = T_\infty + \overbrace{\frac{1}{UA}}^{k_p}\alpha Q$$

$$\tau_p\frac{dT}{dt} + T = T_\infty + k_p\alpha Q$$

$$\tau_p = \frac{mc_p}{UA}$$

$$k_p = \frac{1}{UA}$$

Using Laplace and assuming initial conditions 'zero'

$$T(s) = \frac{1}{\tau_p s+1}T_\infty(s) + \frac{k_p}{\tau_p s+1}\alpha Q(s)$$

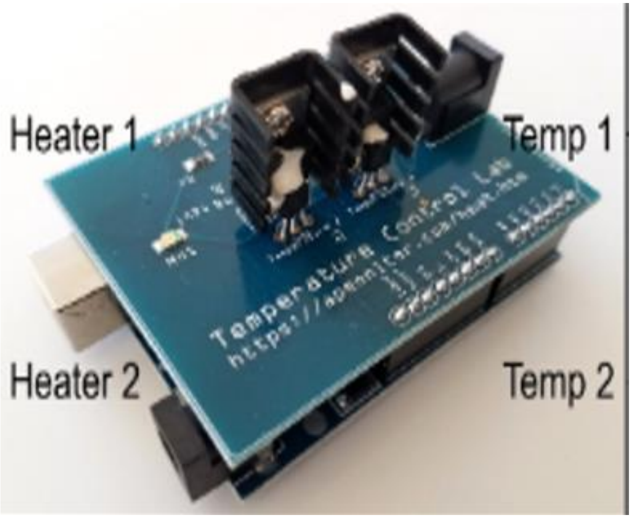
$$T(s) = T_\infty + \frac{k_p}{\tau_p s+1}\alpha Q$$

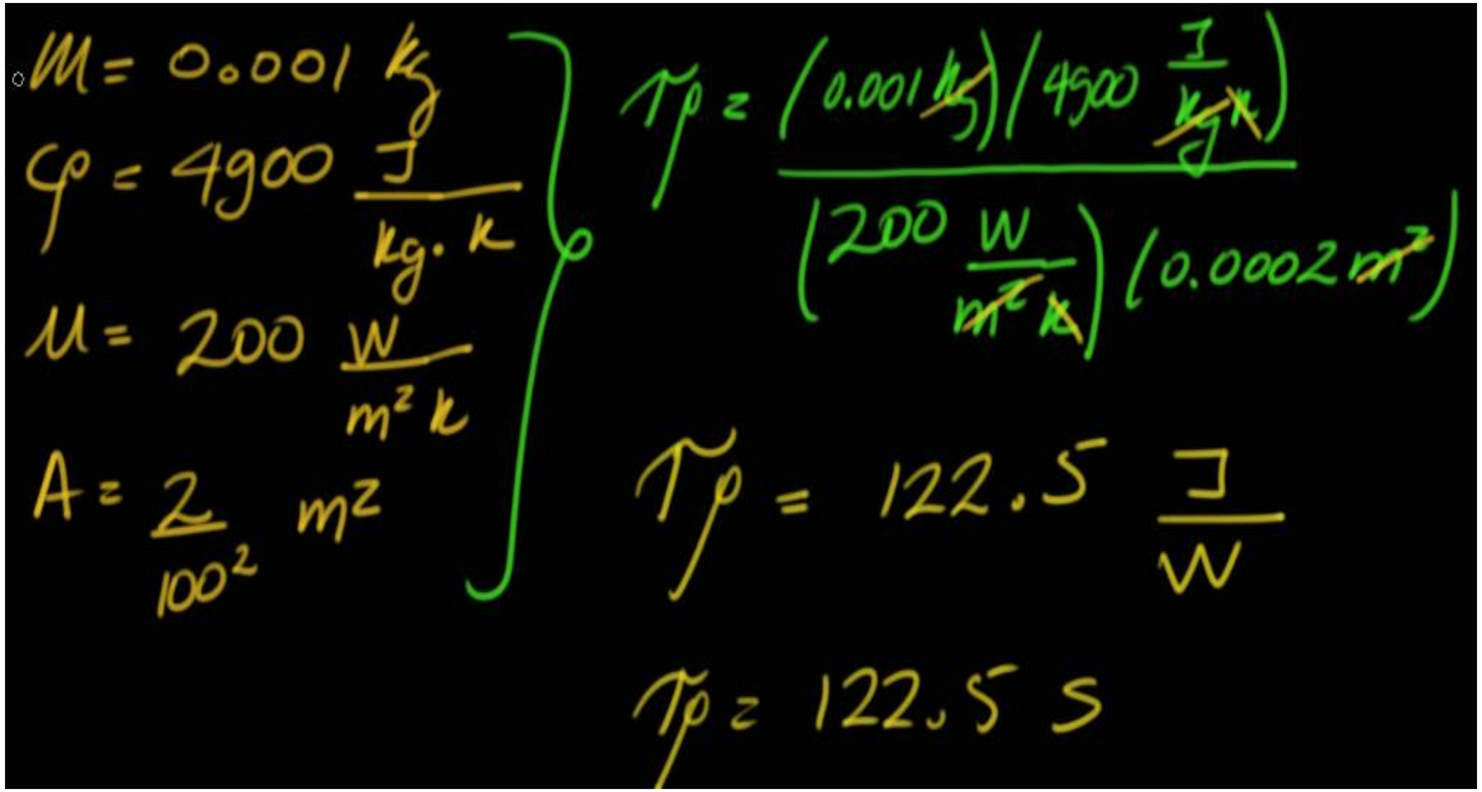
Using *

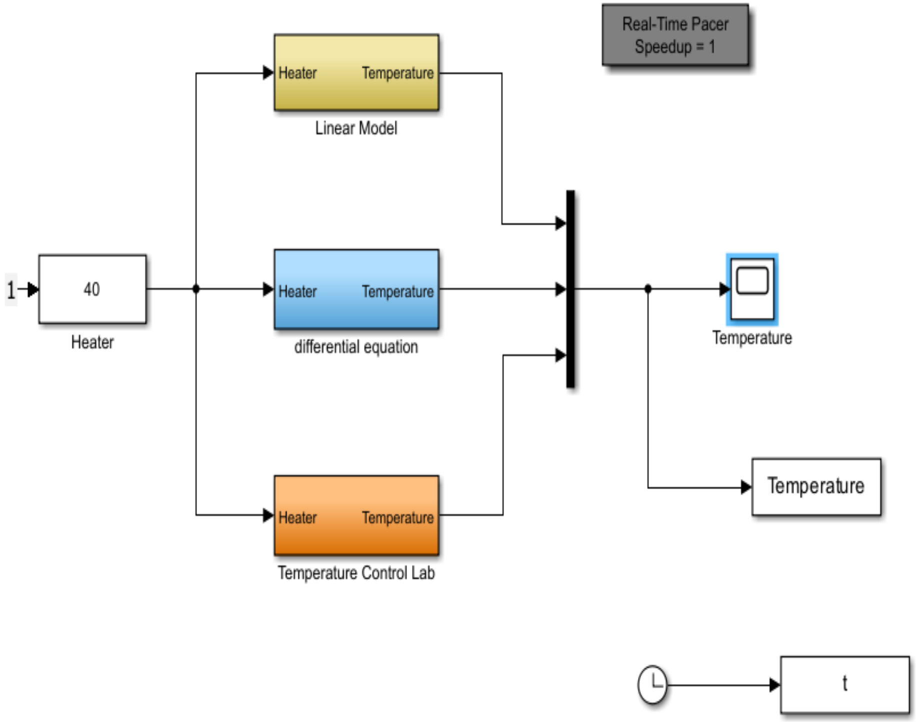
$$\frac{dT}{dt} = \frac{UA(T_\infty - T) + \alpha Q}{mc_p}$$

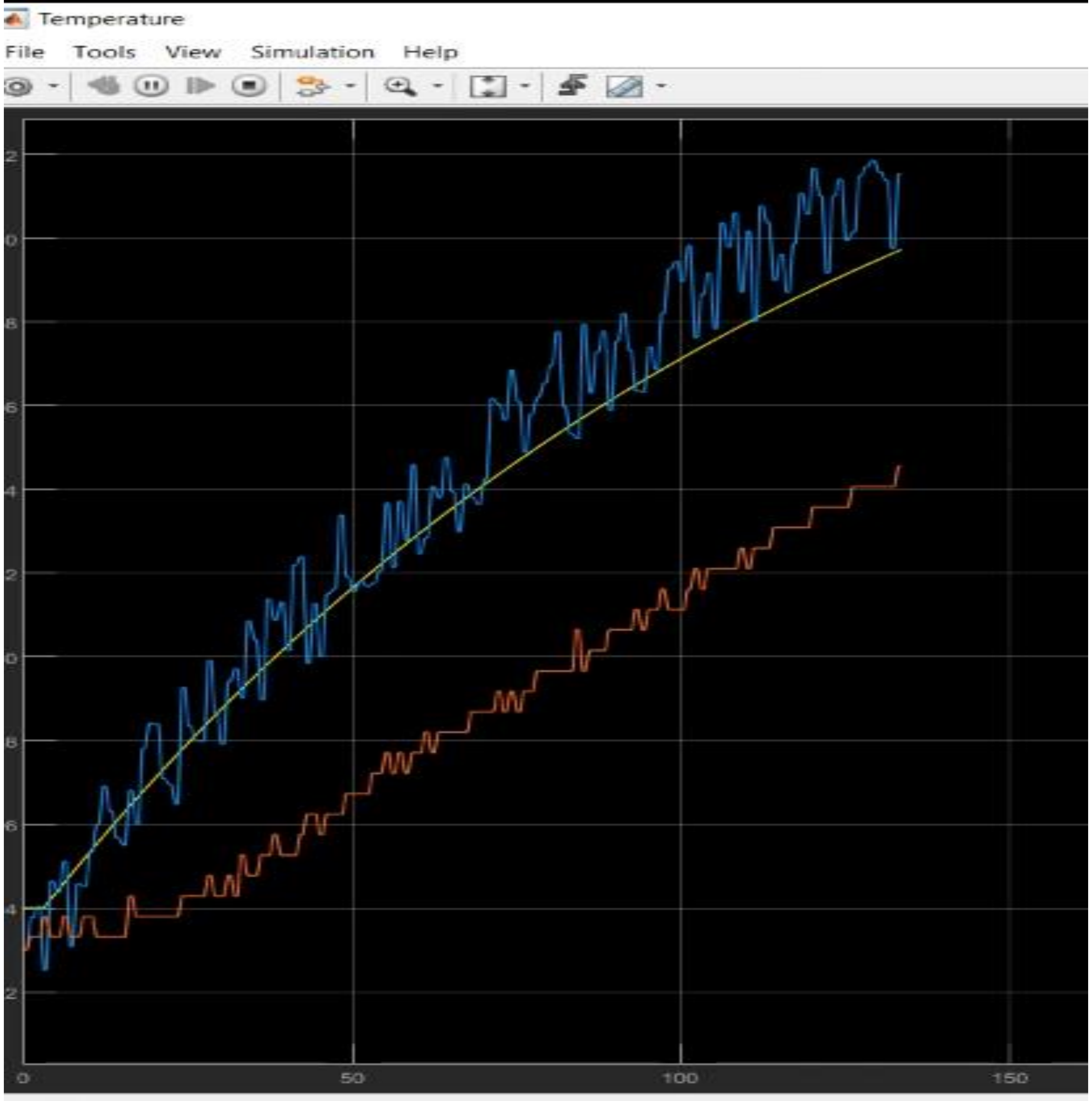
REAL TIME EXPERİMENTS - TC Lab – Dynamic model of a single heater

m = 0.001; % kg (1 gm)
% heat transfer coefficient
U = 200; % W/m^2-K
% surface area
A = 2 / 100^2; % m^2
% heat capacity
Cp = 4900.0; % J/kg-K






Real-Time Pacer
Speedup = 1
Heater
Temperature
Linear Model
1
40
Heater
Heater
Temperature
differential equation
Temperature
Temperature
Heater
Temperature
Temperature Control Lab
t


Temperature
File Tools View Simulation Help
0
50
100
150

Graphical Method: FOPDT to Step Test

A first-order linear system with time delay is a common empirical description of many stable dynamic processes. The equation

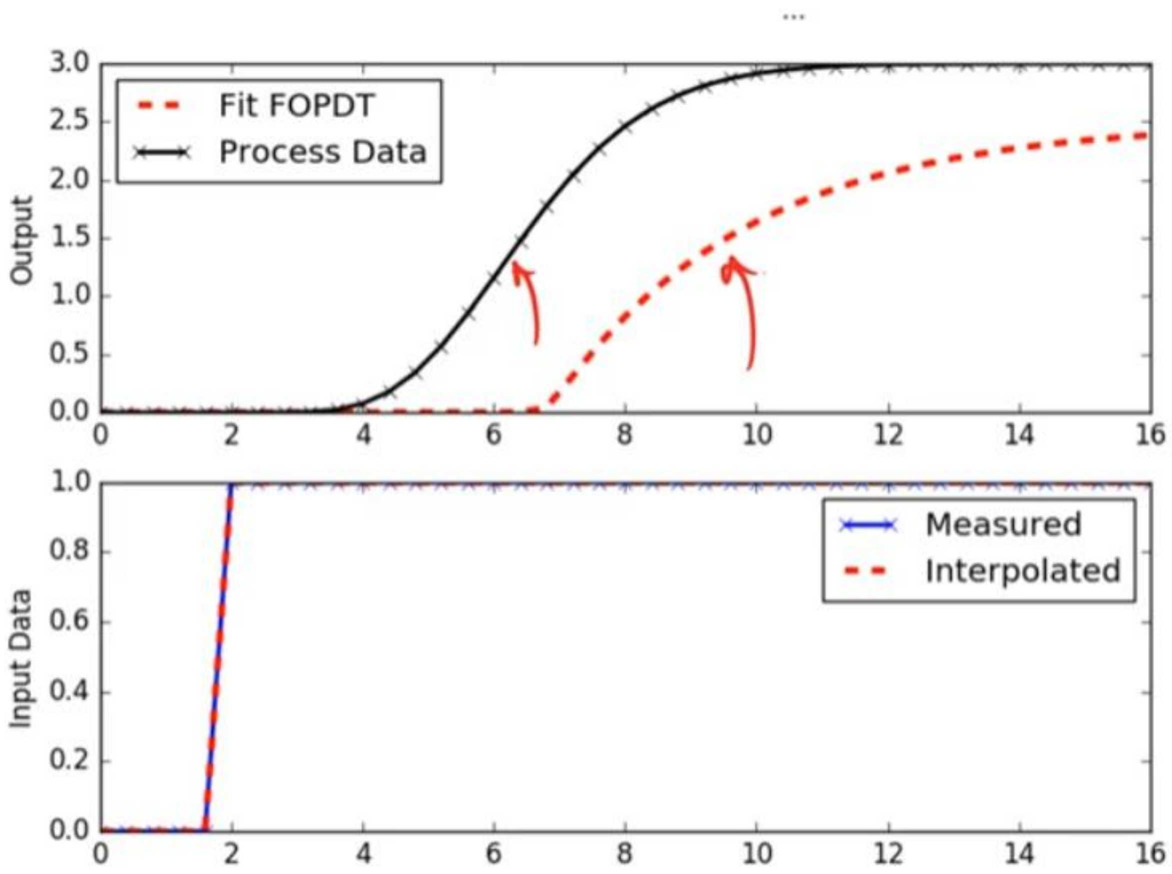
$$\tau_p \frac{dy(t)}{dt} = -y(t) + K_p u\left(t - \theta_p\right)$$

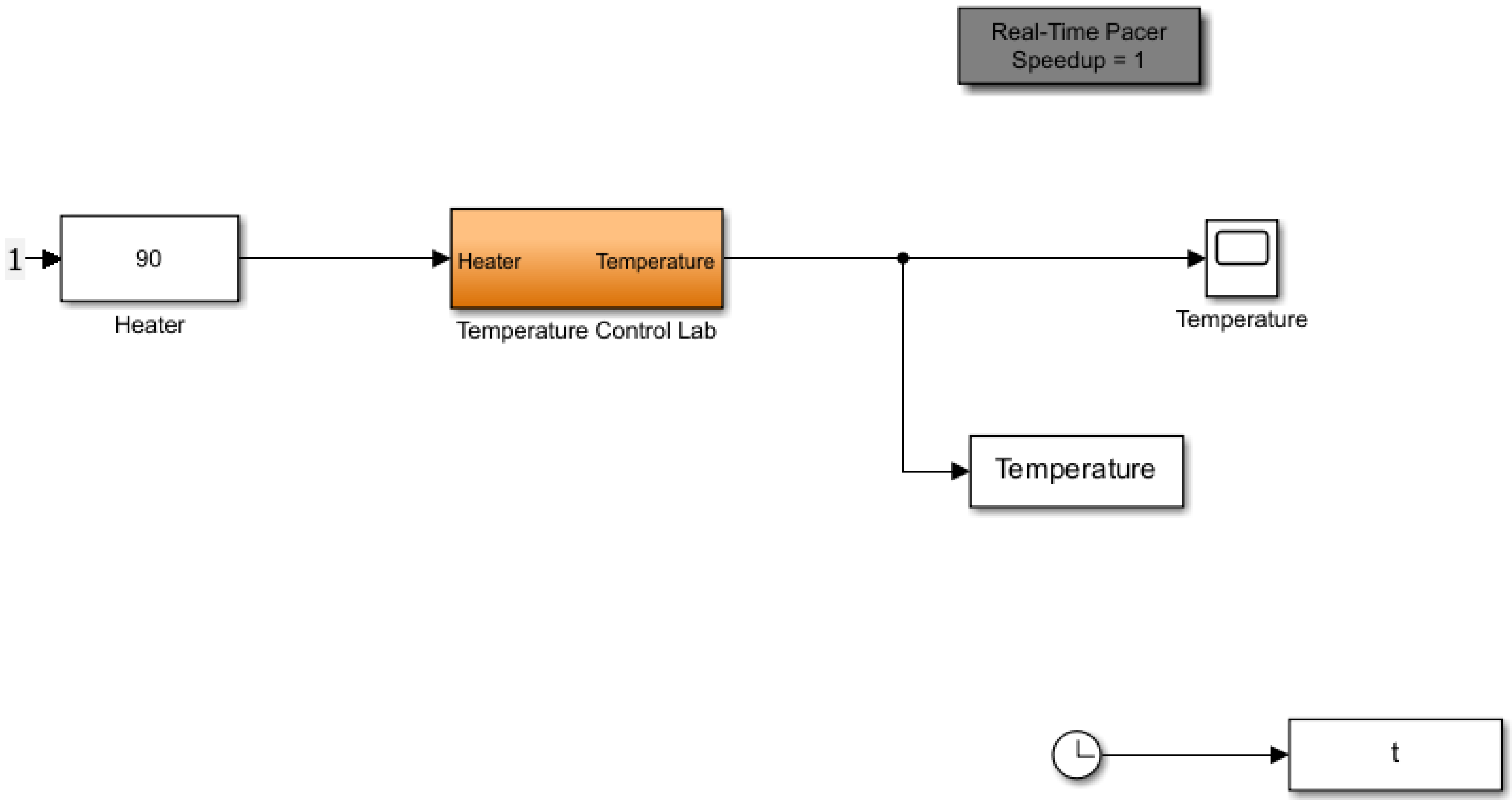
has variables *y(t)* and *u(t)* and three unknown parameters.

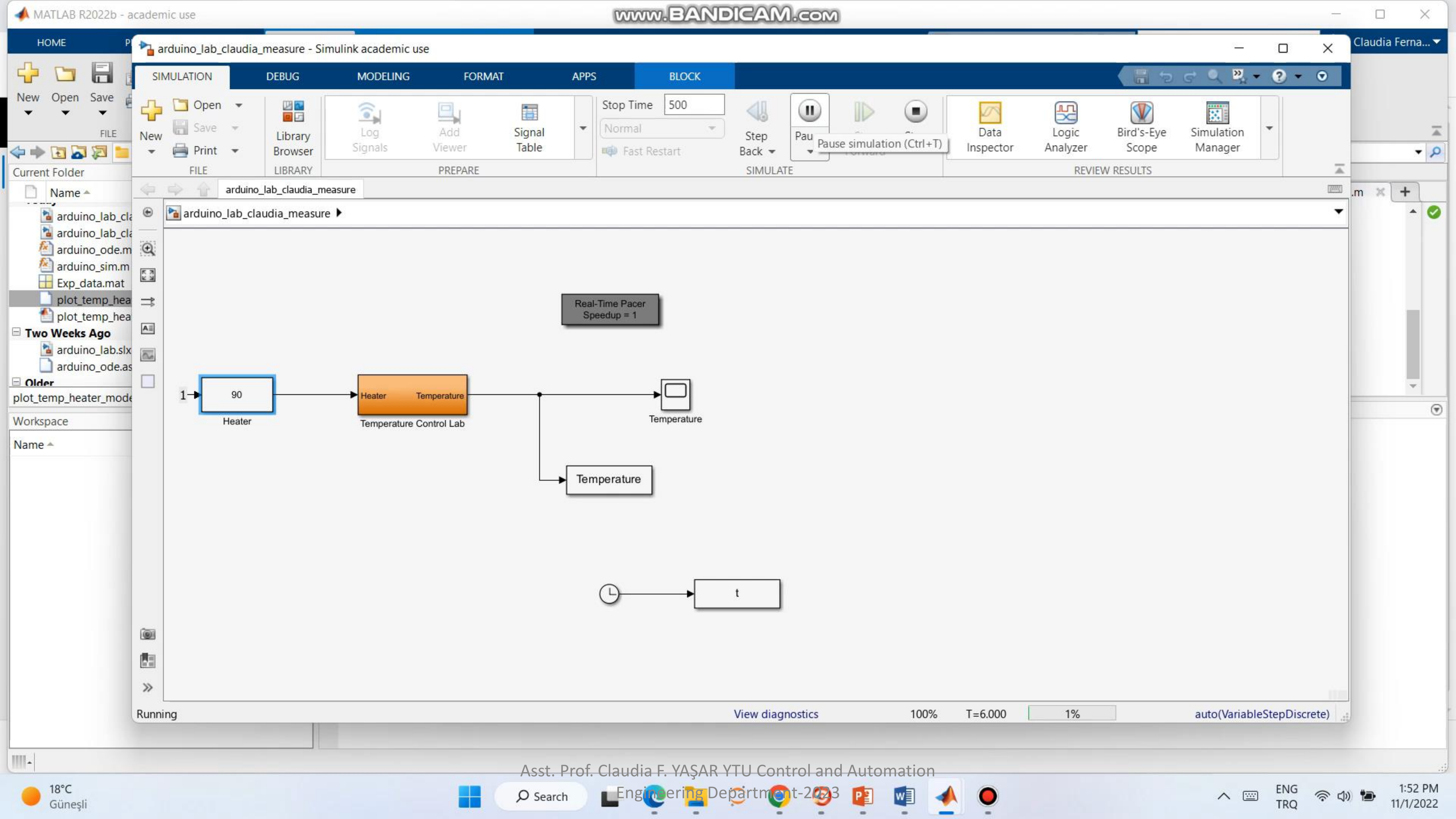
$$K_p \quad = \text{Process gain}$$

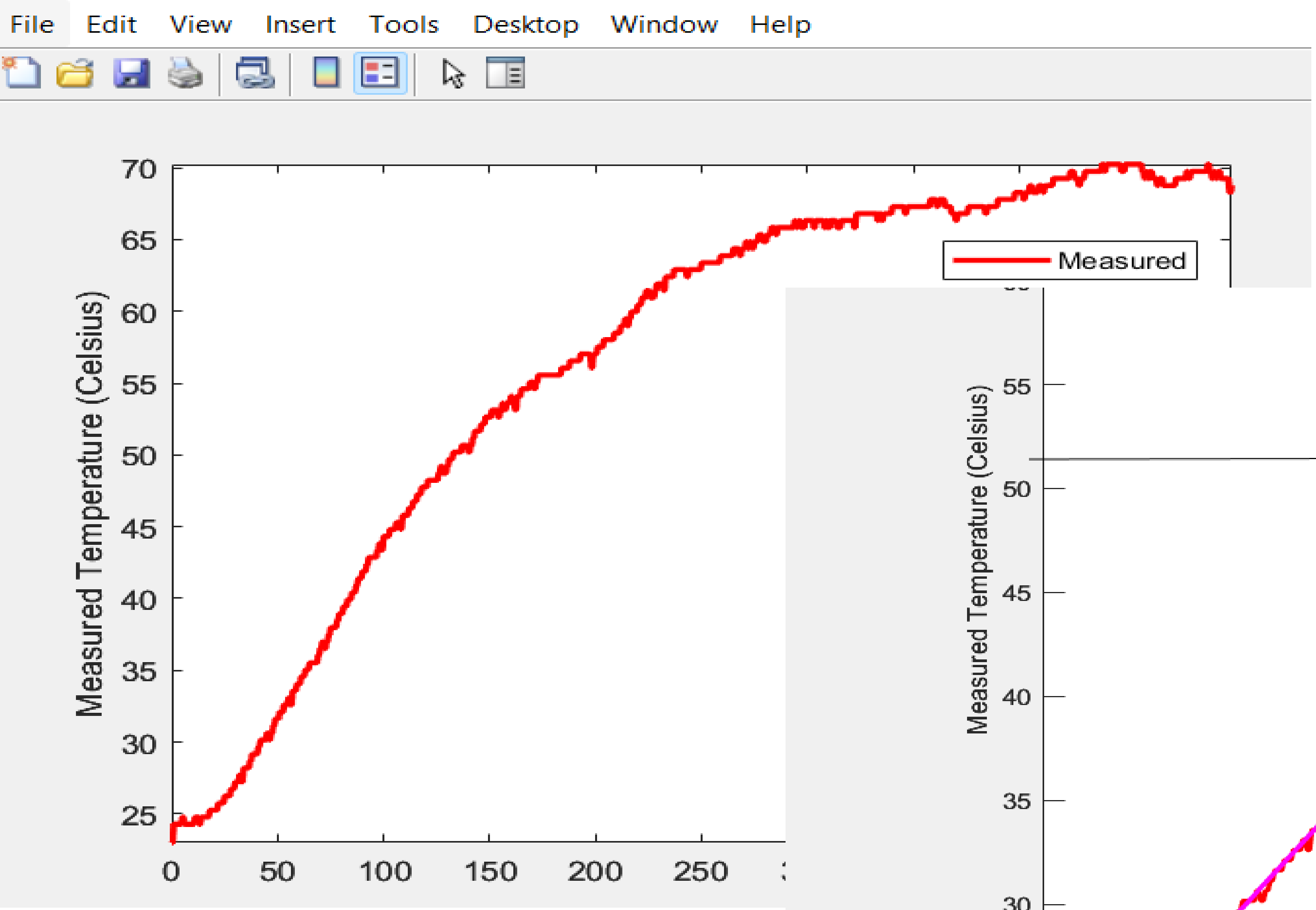
$$\tau_p \quad = \text{Process time constant}$$

$$\theta_p \quad = \text{Process dead time}$$

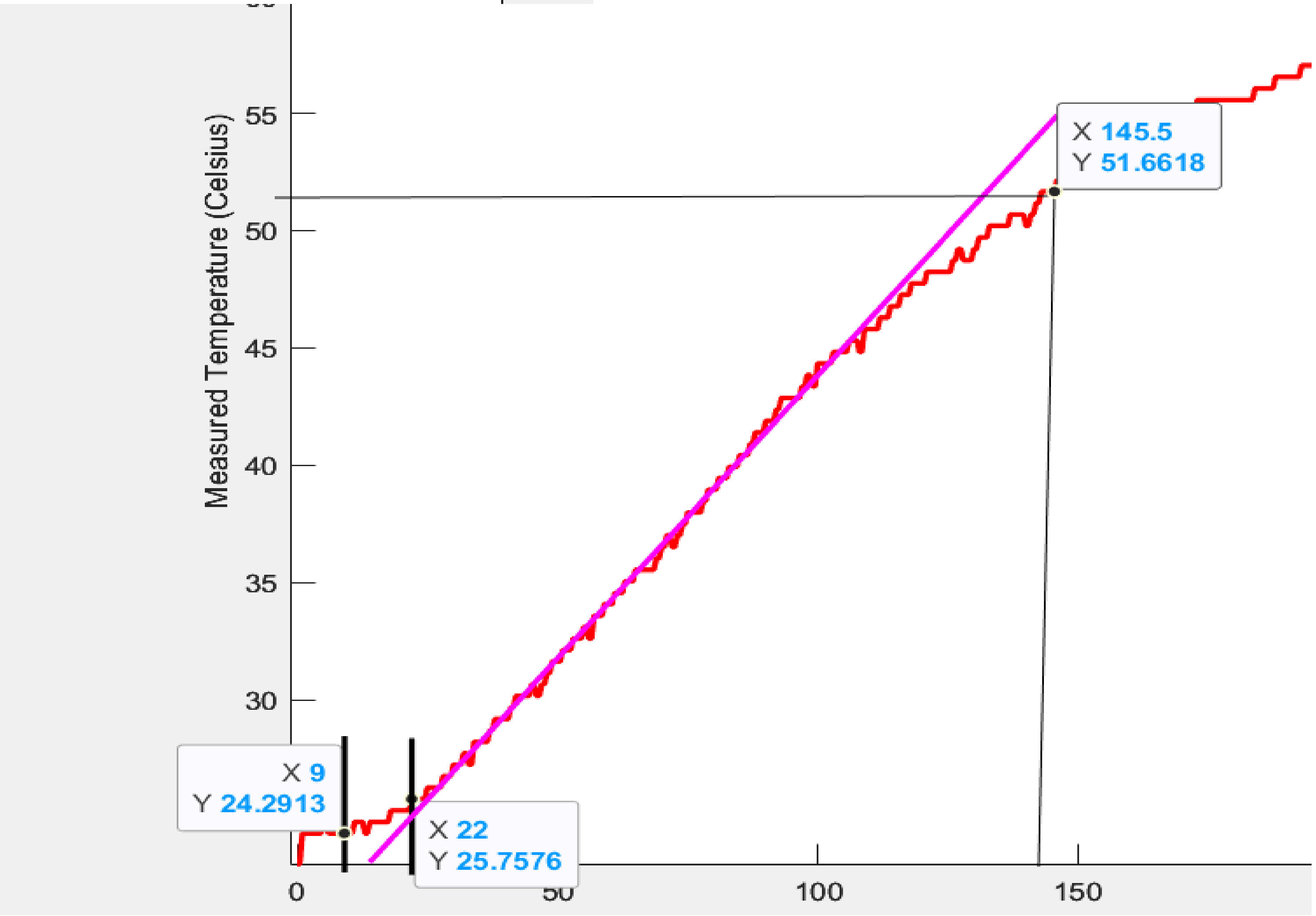



Real-Time Pacer
Speedup = 1
1
90
Heater
Heater
Temperature
Temperature Control Lab
Temperature
Temperature
t


MATLAB R2022b - academic use
arduino_lab_claudia_measure - Simulink academic use
SIMULATION
DEBUG
MODELING
FORMAT
APPS
BLOCK
New
Open
Save
Print
FILE
Library Browser
LIBRARY
Log Signals
Add Viewer
Signal Table
PREPARE
Stop Time
500
Normal
Fast Restart
Step Back
Pause simulation (Ctrl+T)
SIMULATE
Data Inspector
Logic Analyzer
Bird's-Eye Scope
Simulation Manager
REVIEW RESULTS
Current Folder
Name
arduino_ode.m
arduino_sim.m
Exp_data.mat
Two Weeks Ago
arduino_lab.slx
Older
Workspace
arduino_lab_claudia_measure
Real-Time Pacer
Speedup = 1
1
90
Heater
Temperature
Temperature Control Lab
Temperature
Temperature
t
Running
View diagnostics
100%
T=6.000
1%
auto(VariableStepDiscrete)



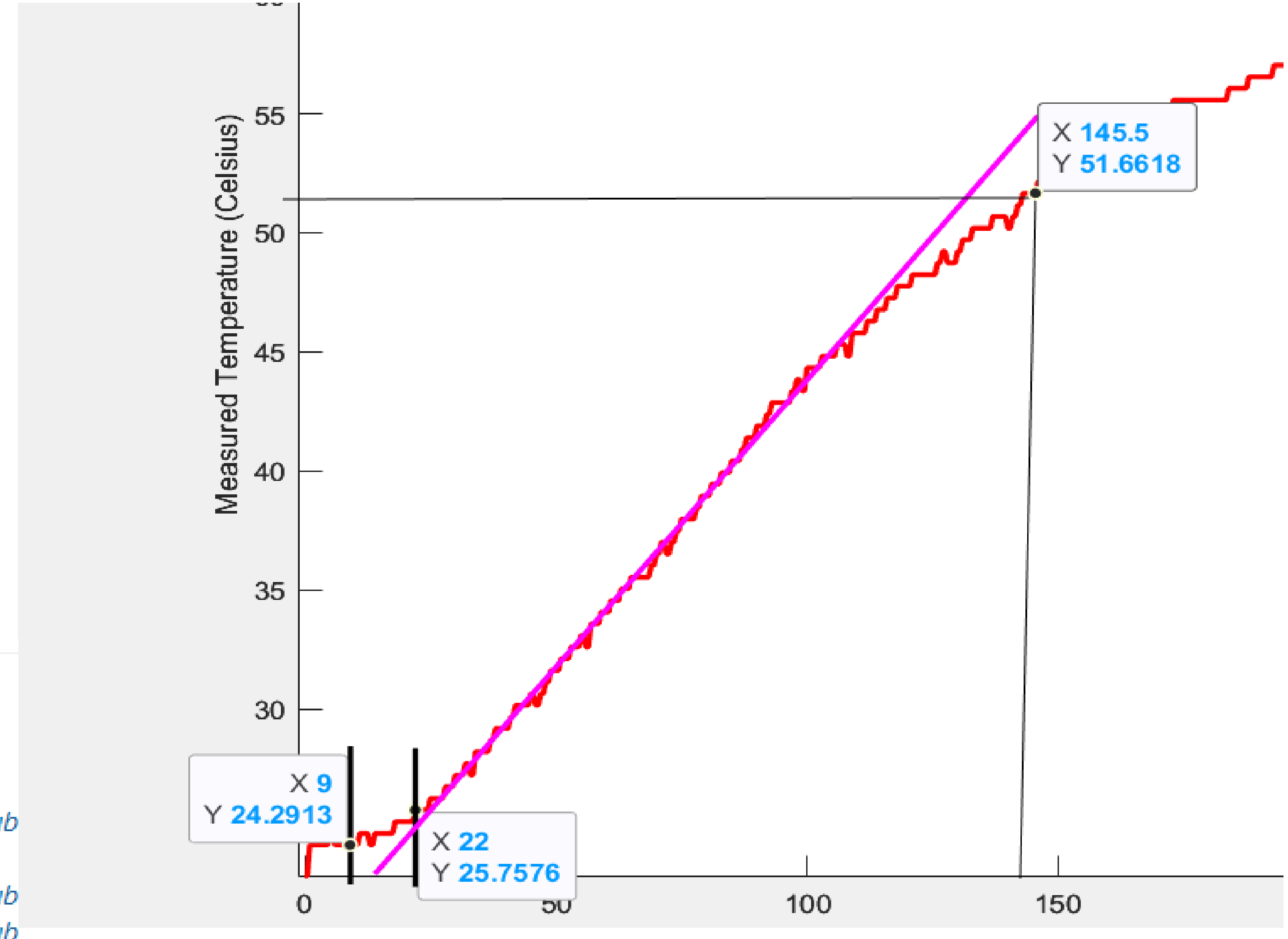
File Edit View Insert Tools Desktop Window Help
70
65
60
55
50
45
40
35
30
25
Measured Temperature (Celsius)
0
50
100
150
200
250
Measured



55
50
45
40
35
30
Measured Temperature (Celsius)
0
50
100
150
X 145.5
Y 51.6618
X 9
Y 24.2913
X 22
Y 25.7576

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%% Plot temperature Exp_2 measurement obtain FOPDT parameters to
%%%%%%%%  a step input
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc;clear all;
load ('Exp_2.mat')
figure(1)
plot(t,Temperature,'r-','LineWidth',2);
ylabel('Measured Temperature (Celsius)');
legend('Measured');
axis tight

dy=Temperature(end)-Temperature(1);
du=90;
Kp=dy/du;
dead_time=22-9;
y_tao=Temperature(1)+0.632*dy;
Tao=145.2-22;
```

dead_time	13
du	90
dy	45.7683
Kp	0.5085
t	*1001x1 doub*
Tao	123.2000
Temperature	*1001x1 doub*
tout	*1001x1 doub*
y_tao	51.9256



Graphical Method: FOPDT to Step Test

Step test data are convenient for identifying an FOPDT model through a graphical fitting method. Follow the following steps when fitting the parameters K_p, τ_p, θ_p to a step response.

1. Find Δy from step response
2. Find Δu from step response
3. Calculate $K_p = \dfrac{\Delta y}{\Delta u}$
4. Find θ_p, apparent dead time, from step response
5. Find $0.632\Delta y$ from step response
6. Find $t_{0.632}$ for $y(t_{0.632}) = 0.632\Delta y$ from step response
7. Calculate $\tau_p = t_{0.632} - \theta_p$. This assumes that the step starts at $t = 0$. If the step happens later, subtract the step time as well.

Semi-Empirical Model Estimation : Regression

System identification using empirical data. The predictions are aligned to the measured values through an optimizer that adjusts the empirical parameters to minimize a sum of squared error or sum of absolute values objective.

The objective is to fit **empirical and physics-based predictions** to the data for a two heater model of the temperature control lab. Parameters are adjusted to minimize the sum of squared errors (SSE) or the integral absolute error (IAE) between the model predicted values and the measured values.

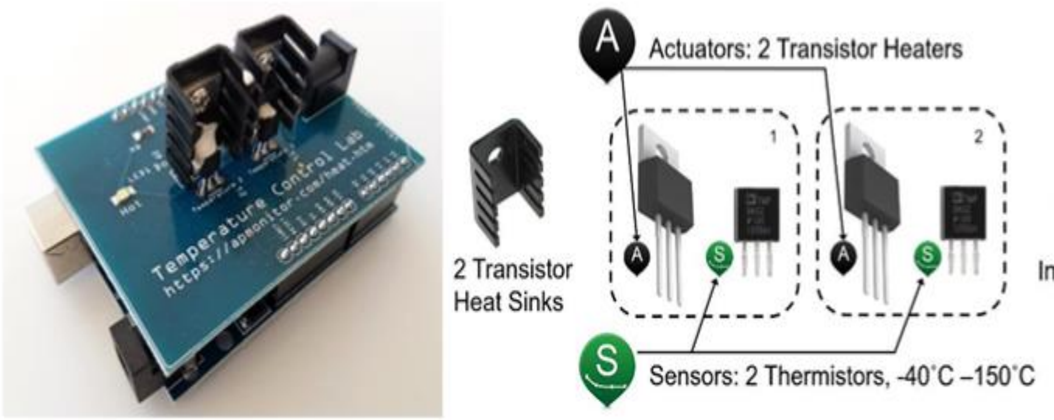
$$IAE_{model} = \sum_{i=0}^{n} \left|T_{1,meas,i} - T_{1,pred,i}\right| + \left|T_{2,meas,i} - T_{2,pred,i}\right|$$

An optimizer is used to adjust the parameters and achieve alignment between the model and the measured values.

https://apmonitor.com/do/index.php/Main/TCLabD

Regression 2nd order MIMO System

Transient model between the two heater power outputs and the two temperature sensors. An energy balance describes the transient temperature response of heaters with temperature sensor.



This model represents the energy balance equation with convective heat transfer, radiative heat transfer, and the heater energy inputs. The additional blue terms are heat transfer

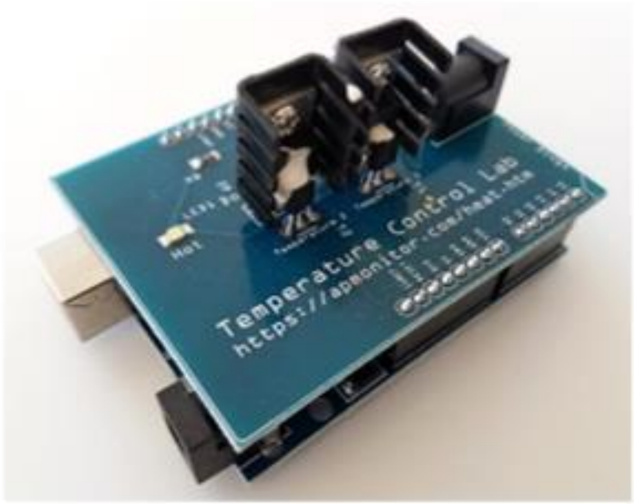
convective radiative heater energy inputs

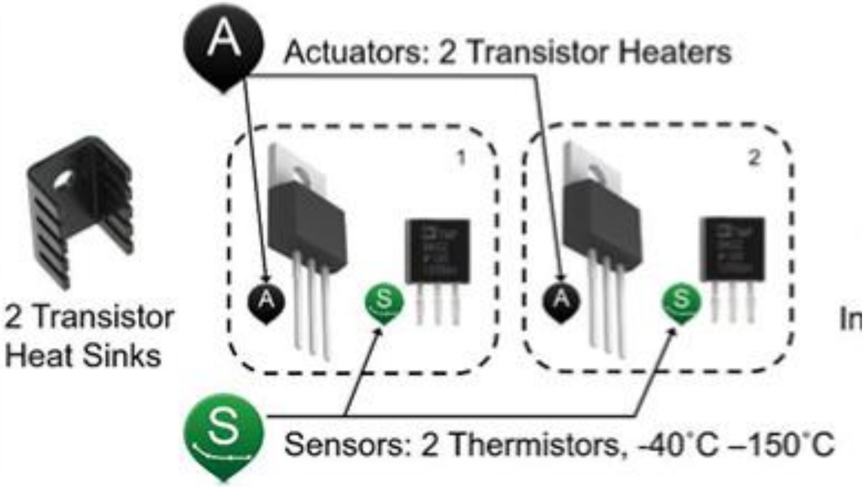
$$mC_p\frac{dT_1}{dt} = UA\left(T_\infty - T_1\right) + \epsilon\sigma A\left(T_\infty^4 - T_1^4\right) + UA_s\left(T_2 - T_1\right) + \epsilon\sigma A_s\left(T_2^4 - T_1^4\right) + Q_1$$

$$mC_p\frac{dT_2}{dt} = UA\left(T_\infty - T_2\right) + \epsilon\sigma A\left(T_\infty^4 - T_2^4\right) + \underbrace{UA_s\left(T_1 - T_2\right) + \epsilon\sigma A_s\left(T_1^4 - T_2^4\right)}_{\text{heat transfer}} + Q_2$$

Regression 2nd order MIMO System

The heater and temperature sensor are assumed to be at the same temperature.





Sensor Model

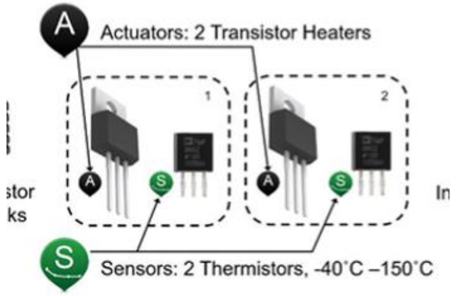
$$\tau_c \frac{dT_{C1}}{dt} = T_1 - T_{C1}$$

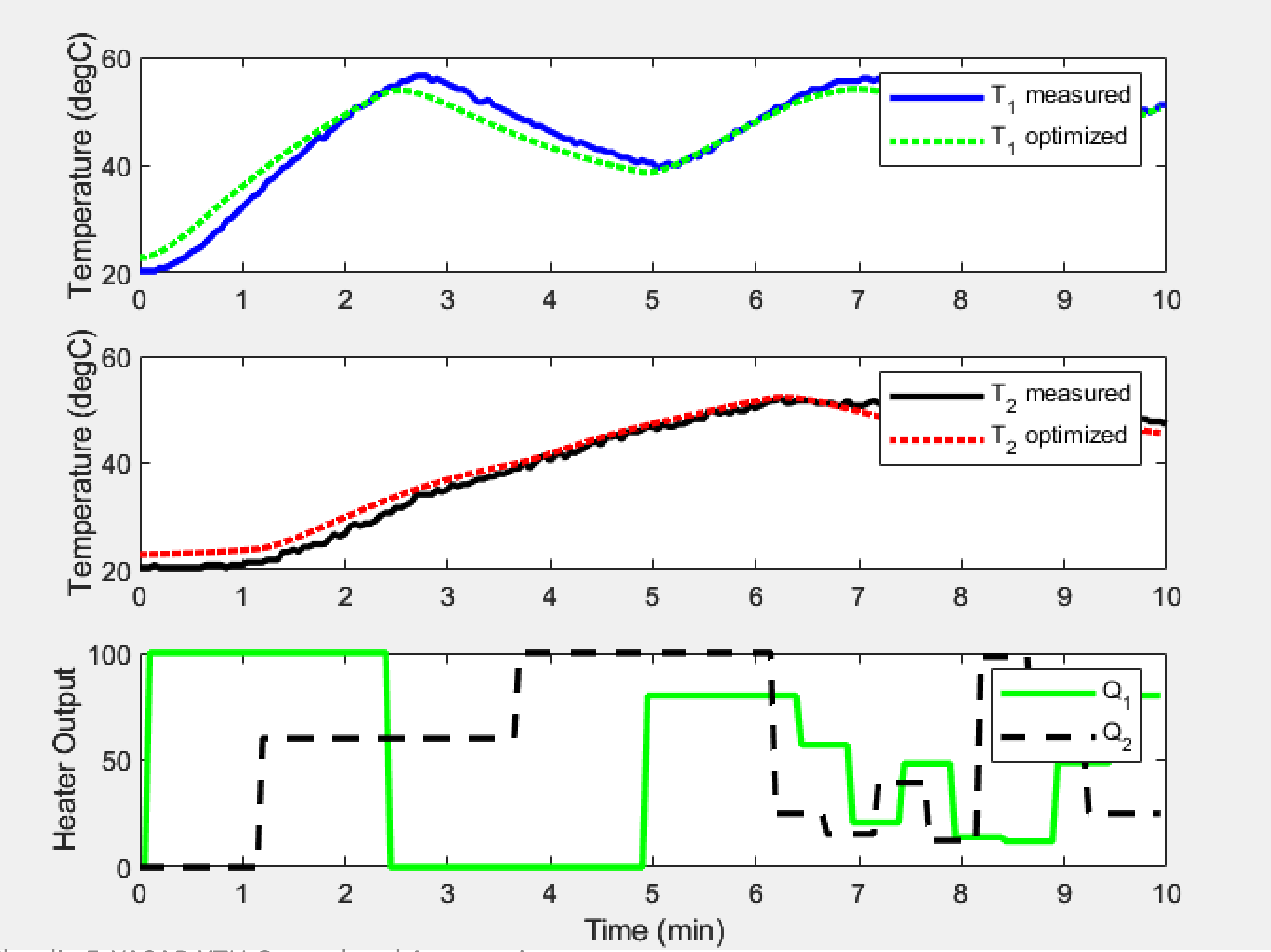
$$\tau_c \frac{dT_{C2}}{dt} = T_2 - T_{C2}$$

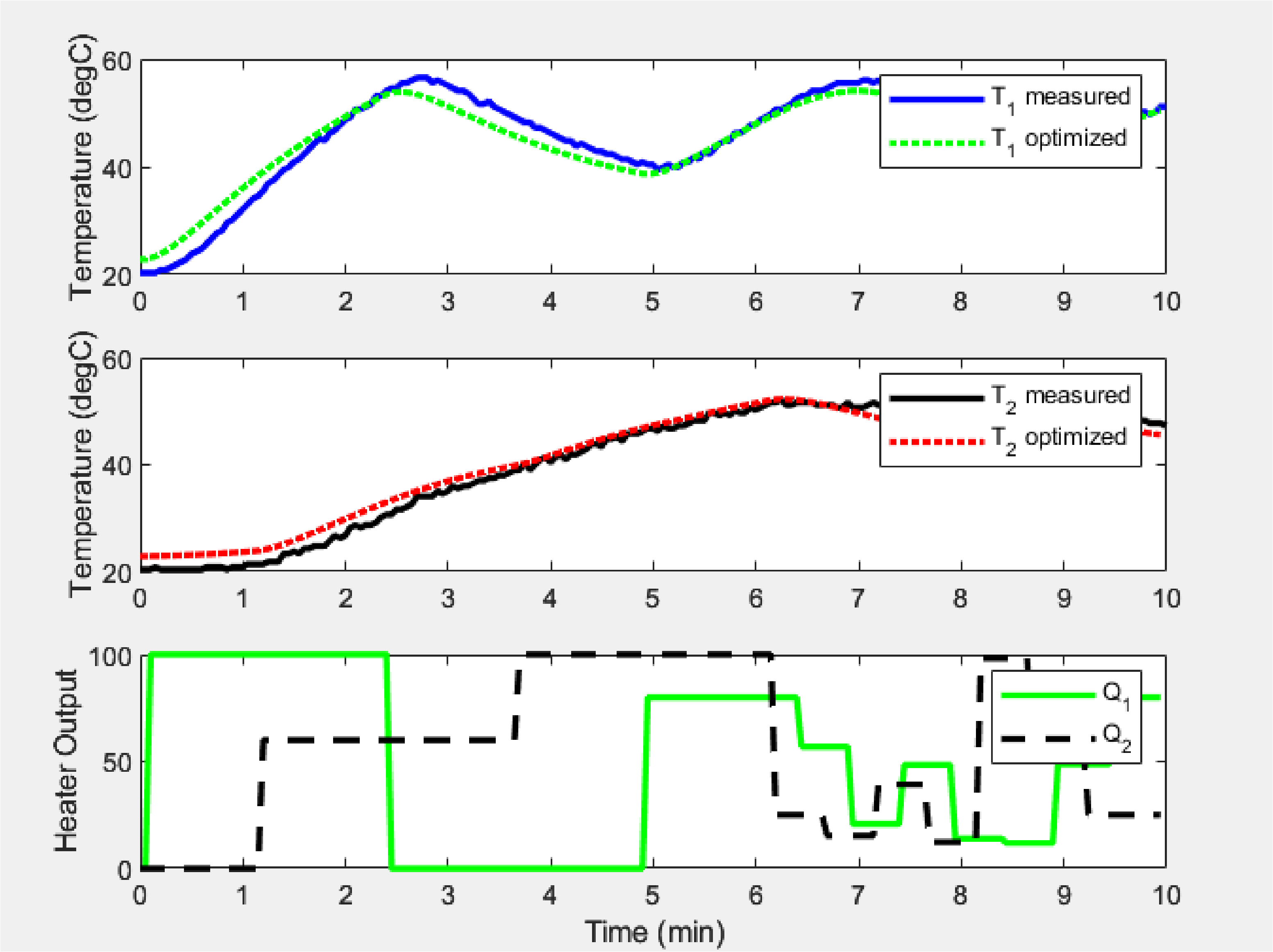
You can assume that conduction is negligible and that the only heat transferred is through radiation to the surroundings or convection or radiation to the surrounding air or from the heater nearby. The heaters are initially off and the heaters and sensors are initially at ambient temperature.

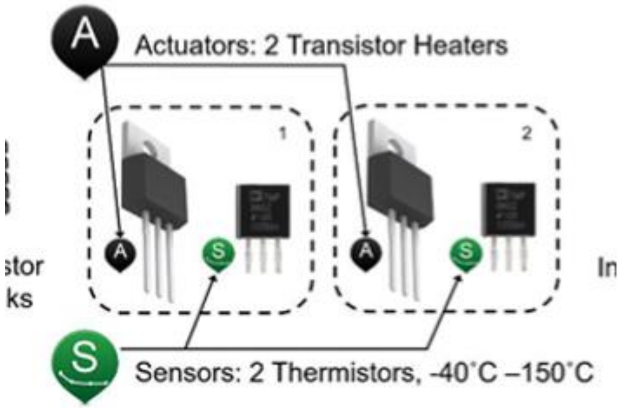
```
Constants
  Ta = 23      ! degC

Parameters
  K1 = 0.607  > 0.1    < 1.0
  K2 = 0.293  > 0.1    < 1.0
  K3 = 0.24   > 0.0001 < 1.0
  tau12 = 192 > 50.0   < 250.0 ! sec
  tau3 = 15   > 10.0   < 20.0  ! sec

Parameters
  Q1 = 0
  Q2 = 0

Variables
  TH1 = Ta
  TH2 = Ta
  TC1 = Ta
  TC2 = Ta

Intermediates
  DT = TH2 - TH1

Equations
  tau12 * $TH1 + (TH1-Ta) = K1*Q1 + K3*DT
  tau12 * $TH2 + (TH2-Ta) = K2*Q2 - K3*DT
  tau3 * $TC1 = -TC1 + TH1
  tau3 * $TC2 = -TC2 + TH2
```

```
K1:    0.69686
K2:    0.42528
K3:    0.41633
tau12:    188.891
tau3:    15
```









K1: 0.69686

K2: 0.42528

K3: 0.41633

tau12: 188.891

tau3: 15