Table of Contents


```
clc;
close all;
clear all;

global a1 a4 p4_p1 gamma1 gamma4 Ms

% initial conditions and parameters

membrane = 0.65; % m
wall = 3.3; % m

R_Air = 286.9; gamma_Air = 1.401;
R_H2 = 4124; gamma_H2 = 1.41;
R_He = 130; gamma_He = 1.66;


T_initial = 21+273.15; % K

Ms = 1.4;

x_testsection = 0:50:200; % m

% p4_p1 = p2_p1*(1 - (gamma4-1)*(a1/a4)*(p2_p1-1)/
sqrt(2*gamma1*(2*gamma1+(gamma1+1)*(p2_p1-1))))^(-2*gamma4/
(gamma4-1));

%constant (back solved)
p4_p1 = 4.9603;
p1 = 101325; %Pa

time = 0:0.0001:0.001;


tic
```

Effects of gas type on flow and shock strength

```
% initialization
R_gases = [R_Air,R_H2,R_He];
gamma_gases = [gamma_Air,gamma_H2,gamma_He];
Labels = {'Air','H_2','He'};
final_x12 = [];
```

```
final_x23 = [];
final_x34 = [];
final_x4 = [];
U  =[];
P = [];
P2_P1 = [];
count = 0;
for i = 1:length(R_gases)
    for j = 1:length(R_gases)
%         if i == j % driven gas = driver gas
            count = count + 1;
            % initialization
            x_12 = [];
            x_23 = [];
            x_34 = [];
            x_4 = [];

            % initial conditions and parameters
            T1 = T_initial;
            T4 = T_initial;
            gamma1 = gamma_gases(i);
            gamma4 = gamma_gases(j);
            R1 = R_gases(i);
            R4 = R_gases(j);

            % speed of sound
            a1 = sqrt(gamma1*R1*T1);
            a4 = sqrt(gamma4*R4*T4);

            %  shock strength
            fun = @nonlinfunc; x0 = 1; x = fsolve(fun,x0);
            p2_p1 = x;

            % other flow quantities
            p3_p4 = p2_p1/p4_p1;
            T3 = T4*(p3_p4)^((gamma4-1)/gamma4);
            T2 = T1*p2_p1*(((gamma1+1)/(gamma1-1)+p2_p1)/(1+(gamma1+1/
(gamma1-1)*p2_p1)));
            a3 = sqrt(gamma4*R4*T3);
            Ms = sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1);

            % velocities of interfaces
            up = (a1/gamma1)*(p2_p1-1)*(2*gamma1/(gamma1+1)/
(p2_p1+(gamma1-1)/(gamma1+1)))^0.5; % contact surface (driver/driven)
 speed
            W = a1*sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1); % shock
 speed
            u3 = up; % driven gas speed
            u_tail = u3-a3; % tail of expansion wave speed
            u_head = -a4; % head of expansion wave speed

            t_experiment = [];
            for x = x_testsection
                t_experiment = [t_experiment,x/up - x/W];
```

```
            end
            for t = time

                % Shock wave location, contact surface, head and tail
 of expansion
                x_12 = [x_12,W*t + membrane];
                x_23 = [x_23,up*t + membrane];
                x_34 = [x_34,u_tail*t + membrane];
                x_4 = [x_4,u_head*t + membrane];

            end

            final_x12 = [final_x12, W*t + membrane];
            final_x23 = [final_x23,up*t + membrane];
            final_x34 = [final_x34,u_tail*t + membrane];
            final_x4 = [final_x4,u_head*t + membrane];


            % figure
            figure,hold on
            set(gcf,'color','w');

            plot(x_12,time), hold on
            plot(x_23,time), hold on
            plot(x_34,time), hold on
            plot(x_4,time), hold on
            xlabel('x [m]');ylabel('time [s]')
            legend('x_1_2','x_2_3','x_3_4','x_4','location','best')
            title(strcat('Driver: ',Labels(j),' | Driven:
 ',Labels(i)));%,'R=(',num2str(R_gases(j)),'); Driven =
 ',Labels(i),'R=(',num2str(R_gases(i)),')'))

            figure, hold on
            set(gcf,'color','w');

            bar([T1,T2,T3,T4],'b')
            set(gca,'XTick',1:4,'XTickLabel',
{'T_1','T_2','T_3','T_4'})
            title(strcat('Driver: ',Labels(j),' | Driven:
 ',Labels(i)),'fontsize',12);%,'R=(',num2str(R_gases(j)),'); Driven =
 ',Labels(i),'R=(',num2str(R_gases(i)),')'))
            ylabel('Temperature [K]')


            U = [U,up];
            P = [P, p2_p1*p1];
            P2_P1 = [P2_P1,p2_p1];


            figure(59),hold on
            set(gcf,'color','w');

            plot(x_testsection,t_experiment,'color',[rand(1) rand(1)
 rand(1)]), hold on
```

```
            xlabel('test section [m]') % relative to membrane
            ylabel('test time [s]')
            title('Supersonic Wind Tunnel')



%         end

    end
end

figure(59), hold on
legend('Air | Air', 'Air | H_2', 'Air | He','H_2 |
 Air','H_2 | H_2', 'H_2 | He', 'He | Air', 'He | H_2', 'He |
 He','location','best');


figure
set(gcf,'color','w');

bar(U,'b')
set(gca,'XTick',1:9,'XTickLabel',{'Air | Air', 'Air | H_2', 'Air |
 He','H_2 | Air','H_2 | H_2', 'H_2 | He', 'He | Air', 'He | H_2', 'He
 | He'});

title(strcat('Driver: ',Labels(j),' | Driven:
 ',Labels(i)),'fontsize',12);%,'R=(',num2str(R_gases(j)),'); Driven =
 ',Labels(i),'R=(',num2str(R_gases(i)),')'))
ylabel('Velocity (U_2=U_3) [m/s]')
xlabel('Driver Gas | Driven Gas')

figure
set(gcf,'color','w');

bar(P2_P1,'b')
set(gca,'XTick',1:9,'XTickLabel',{'Air | Air', 'Air | H_2', 'Air |
 He','H_2 | Air','H_2 | H_2', 'H_2 | He', 'He | Air', 'He | H_2', 'He
 | He'});

title(strcat('Driver: ',Labels(j),' | Driven:
 ',Labels(i)),'fontsize',12);%,'R=(',num2str(R_gases(j)),'); Driven =
 ',Labels(i),'R=(',num2str(R_gases(i)),')'))
ylabel('Shock Strength (P_2/P_1)')
xlabel('Driver Gas | Driven Gas')


figure
set(gcf,'color','w');

bar(P,'b')
set(gca,'XTick',1:9,'XTickLabel',{'Air | Air', 'Air | H_2', 'Air |
 He','H_2 | Air','H_2 | H_2', 'H_2 | He', 'He | Air', 'He | H_2', 'He
 | He'});
```

```
title(strcat('Driver: ',Labels(j),' | Driven:
 ',Labels(i)),'fontsize',12);%,'R=(',num2str(R_gases(j)),'); Driven =
 ',Labels(i),'R=(',num2str(R_gases(i)),')'))
ylabel('Pressure (P_2=P_3) [Pa]')
xlabel('Driver Gas | Driven Gas')
% strad = {'Driver = Air; Driven = Air', 'Driver = Air; Driven = H_2',
 'Driver = Air; Driven = He','Driver = H_2; Driven = Air','Driver =
 H_2; Driven = H2', 'Driver = H_2; Driven = He', 'Driver = He; Driven
 = Air', 'Driver = He; Driven = H_2', 'Driver = He; Driven = He'};


%
 legend(strad(1),strad(2),strad(3),strad(4),strad(5),strad(6),strad(7),strad(8),st
% legend('Driver = Air; Driven = H_2')
% legend('Driver = Air; Driven = He')

%}
```

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

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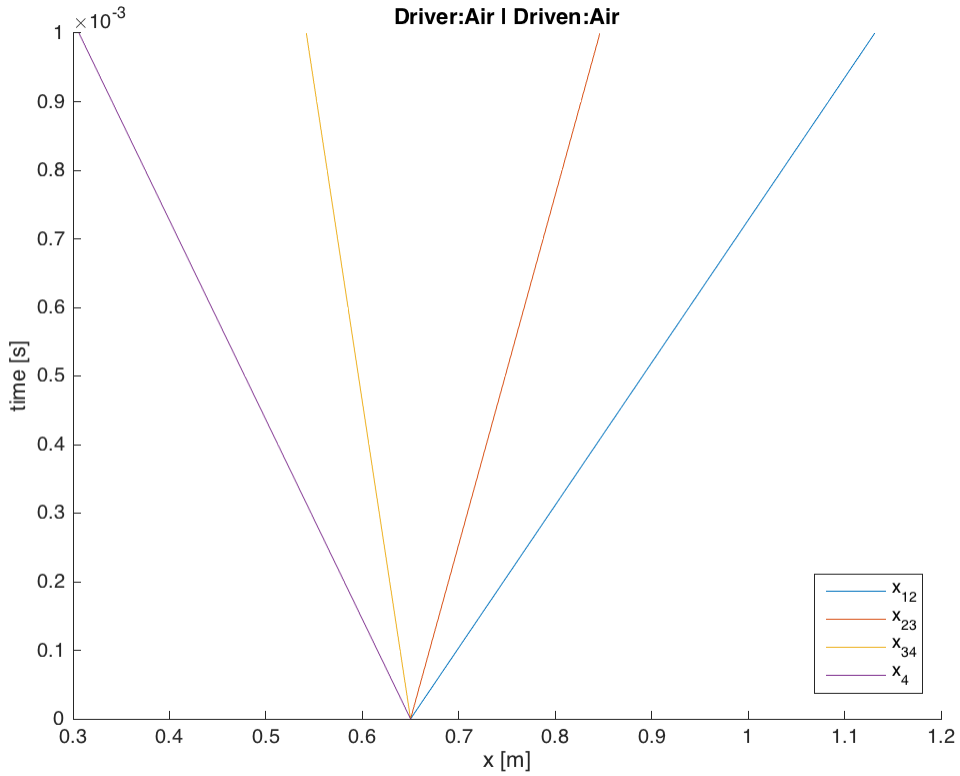
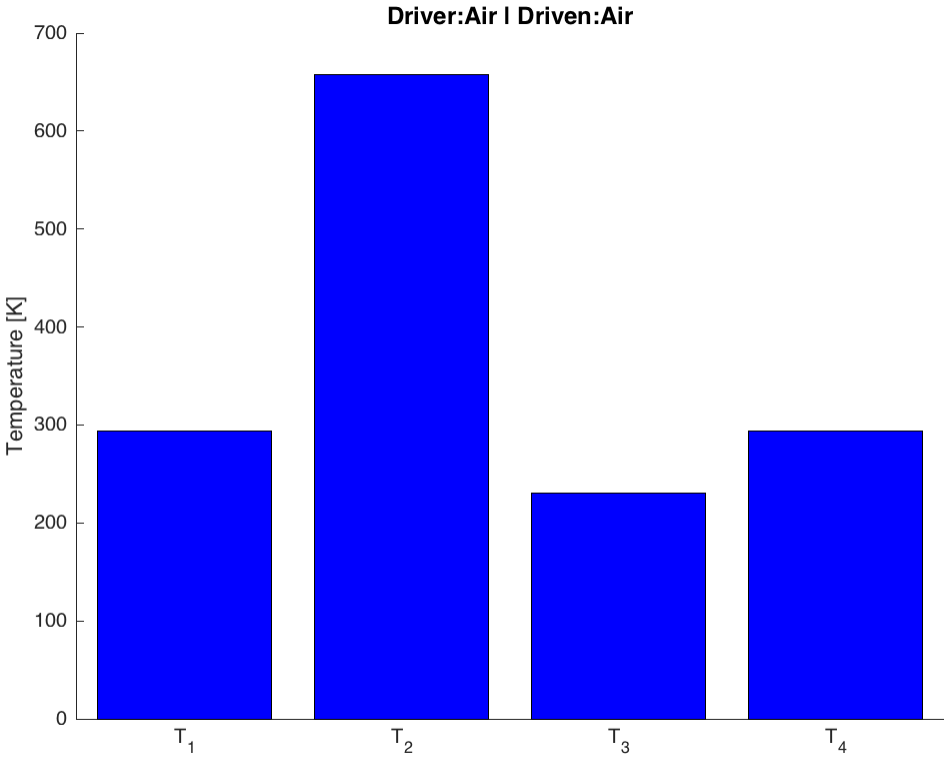
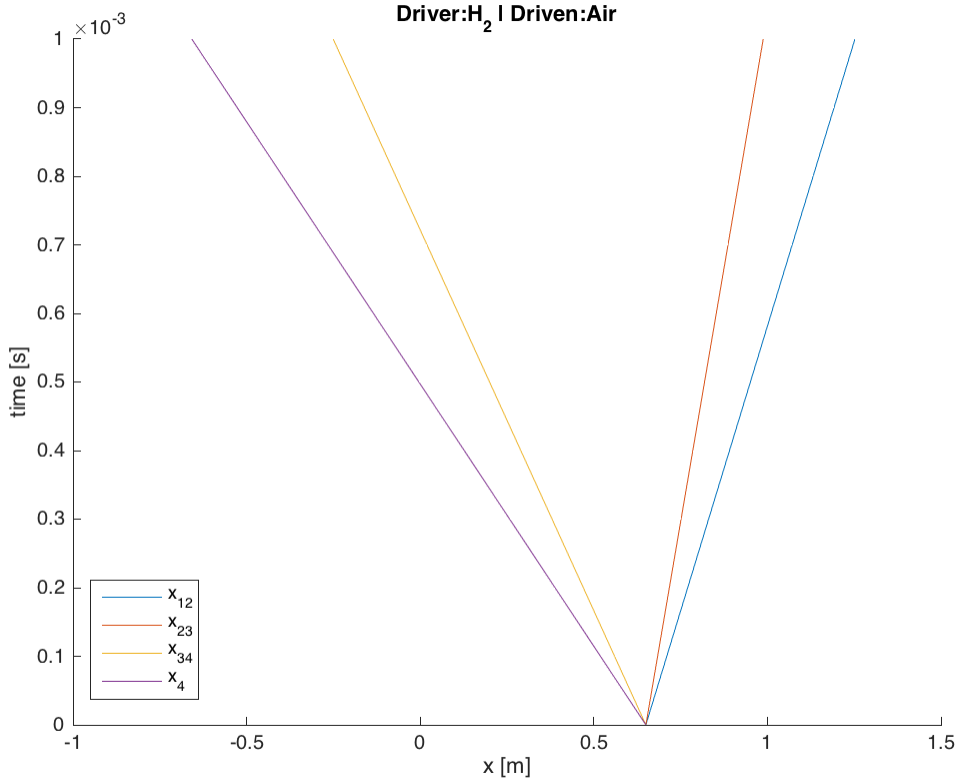
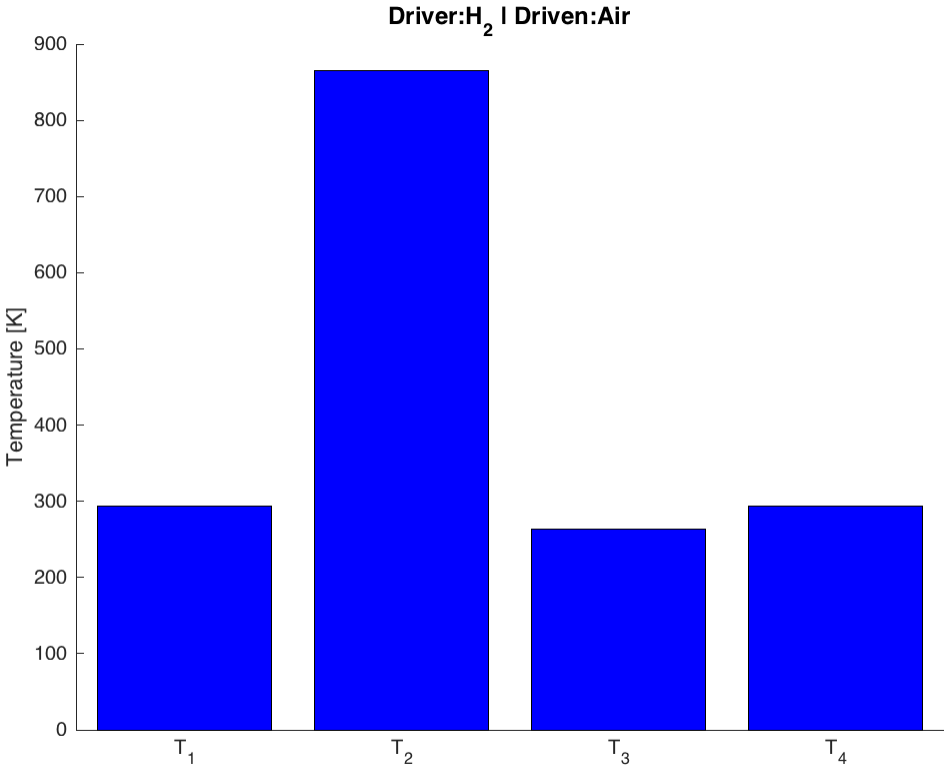
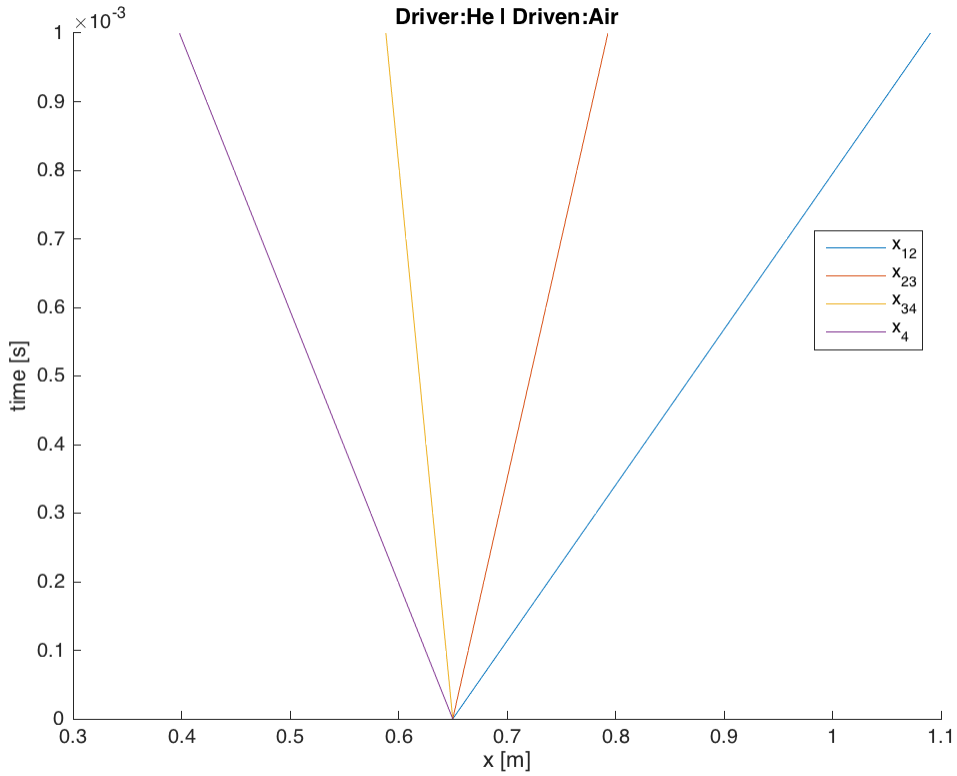
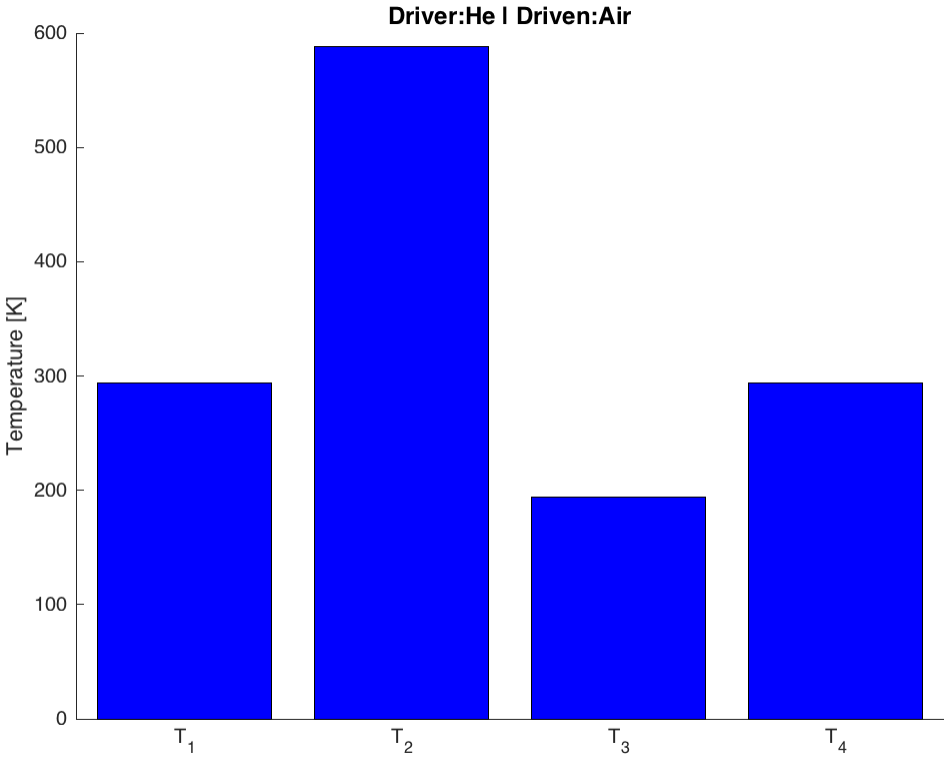

Driver:Air I Driven:Air
×10^-3
time [s]
x [m]
x12
x23
x34
x4

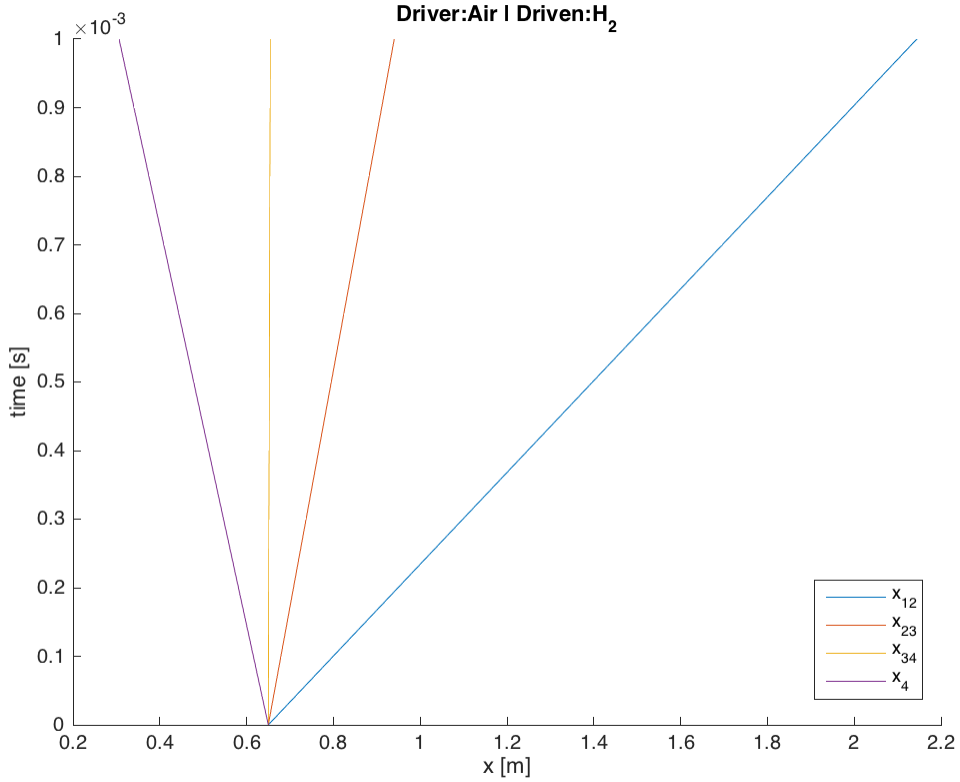

Driver:Air I Driven:Air
Temperature [K]
T1
T2
T3
T4

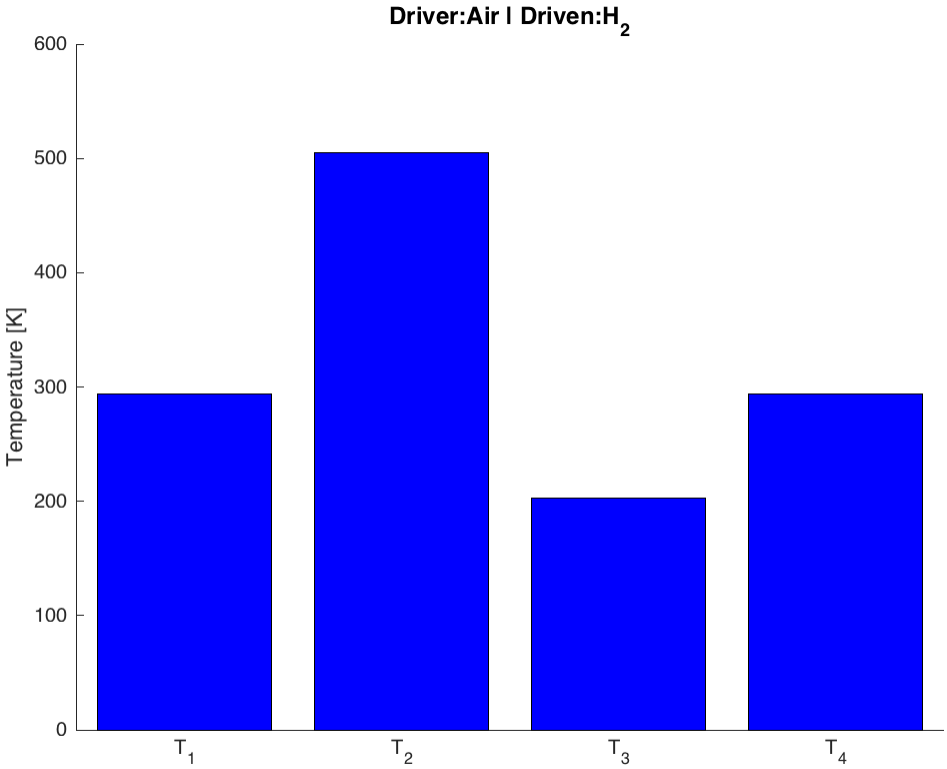

Driver:H2 I Driven:Air
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
x12
x23
x34
x4
-1
-0.5
0
0.5
1
1.5
x [m]

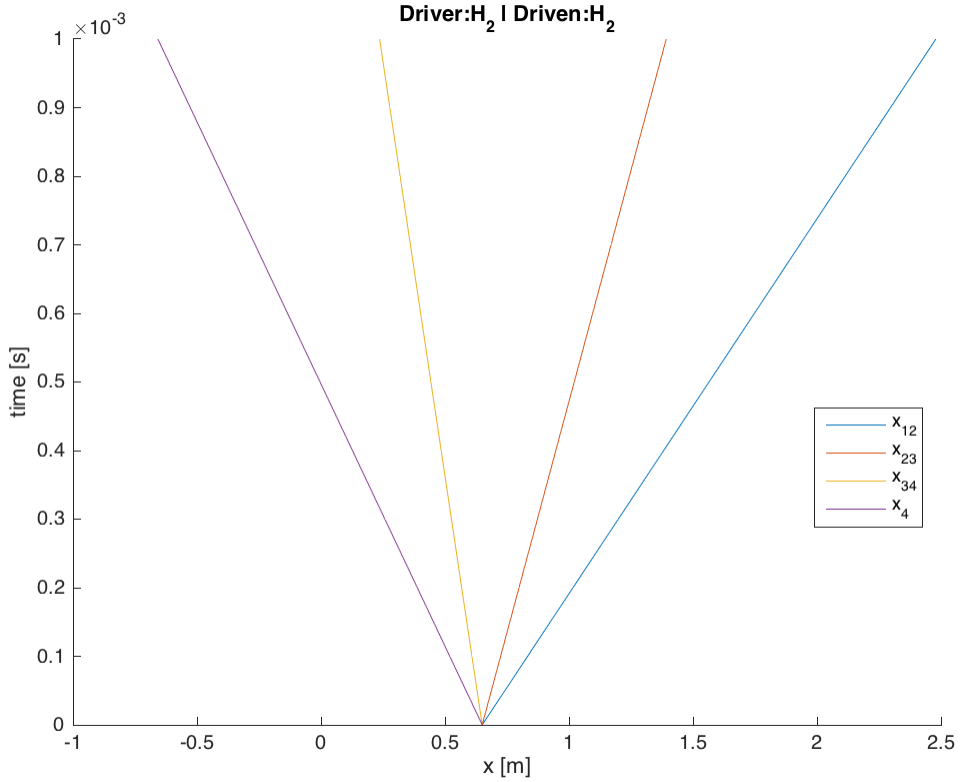

Driver:H2 I Driven:Air
900
800
700
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4

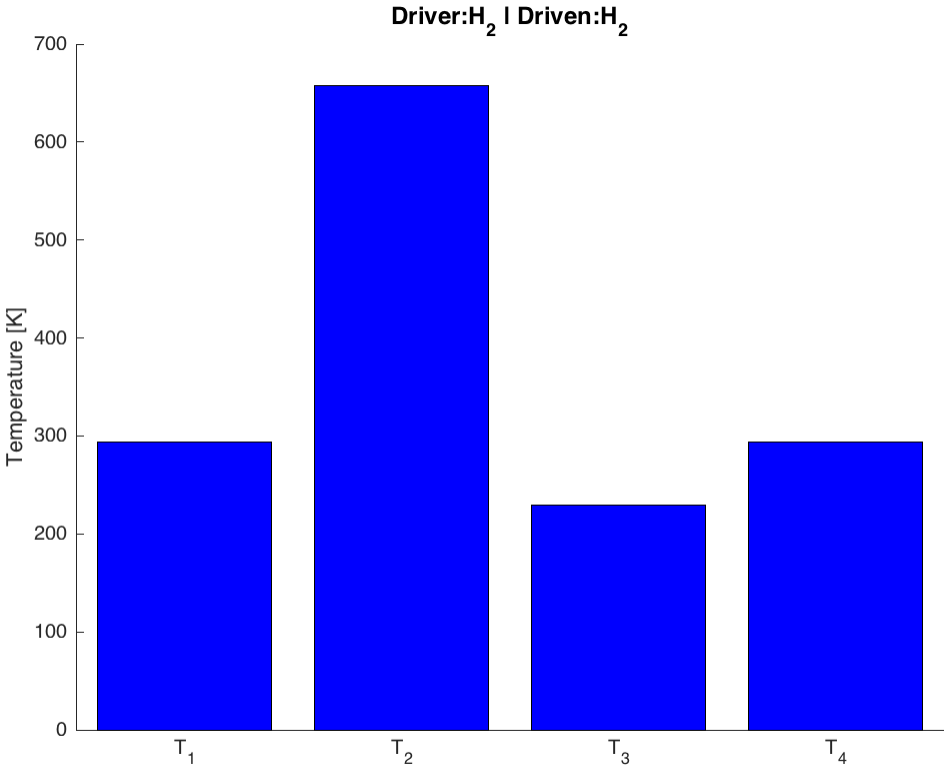

Driver:He I Driven:Air
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
x [m]
x12
x23
x34
x4

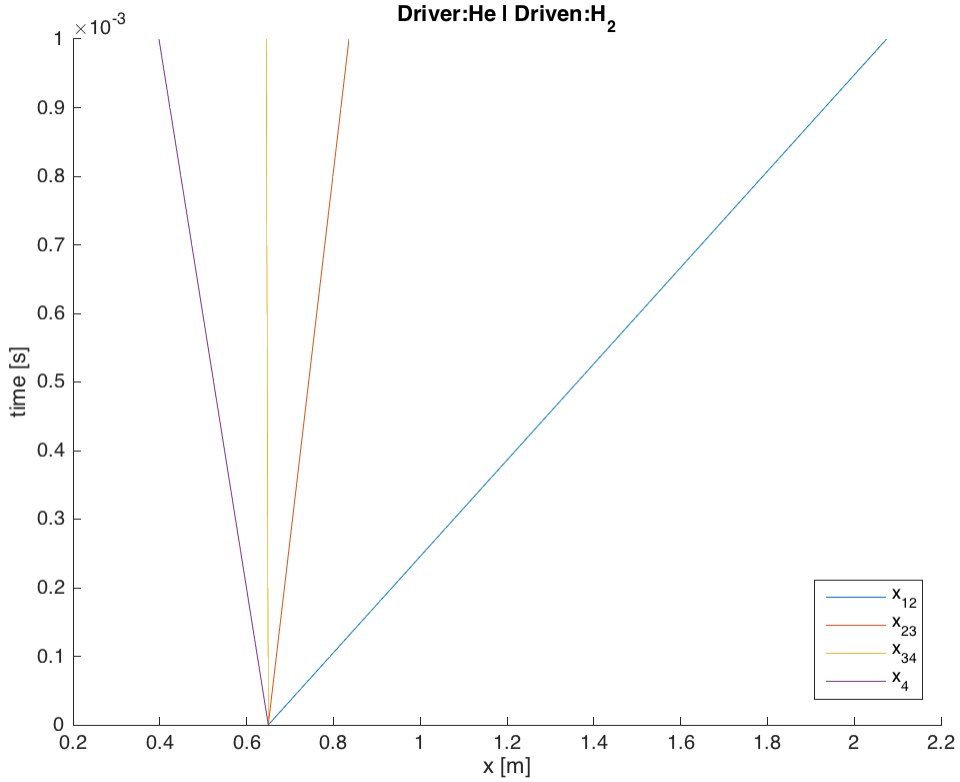

Driver:He I Driven:Air
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4

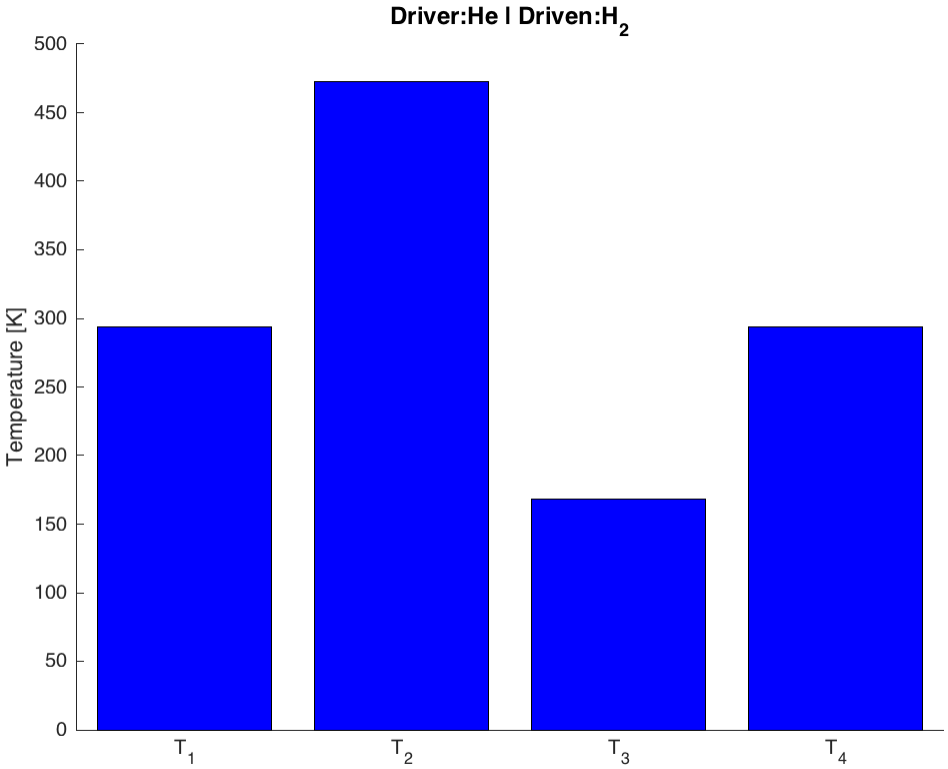

Driver:Air I Driven:H2
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
x [m]
x12
x23
x34
x4

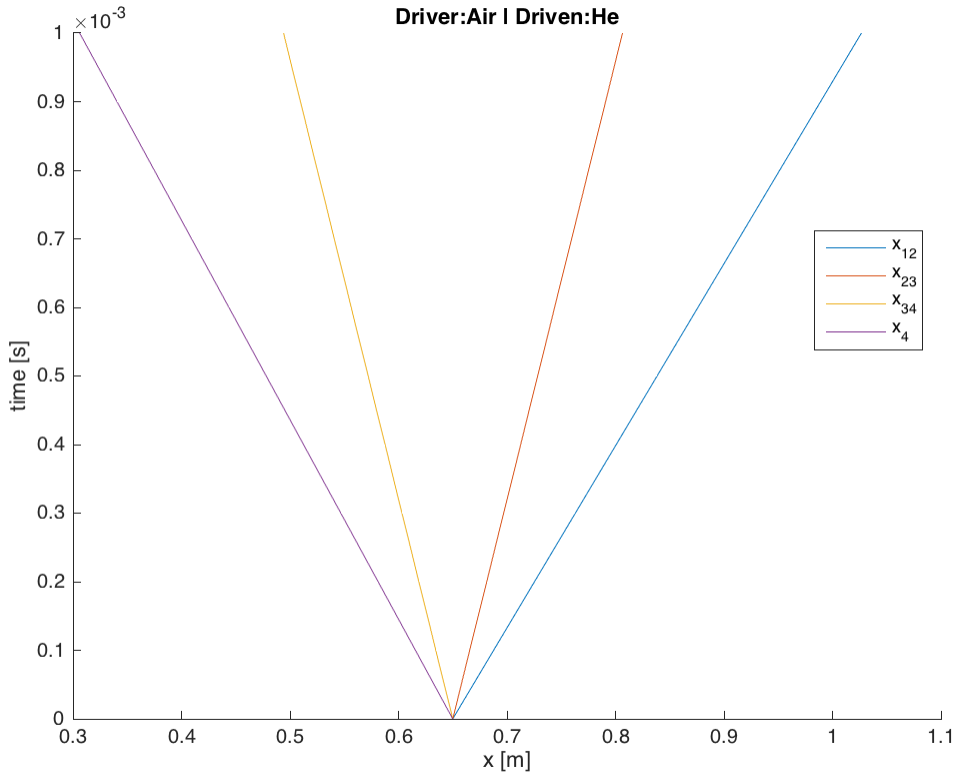

Driver:Air I Driven:H2
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4

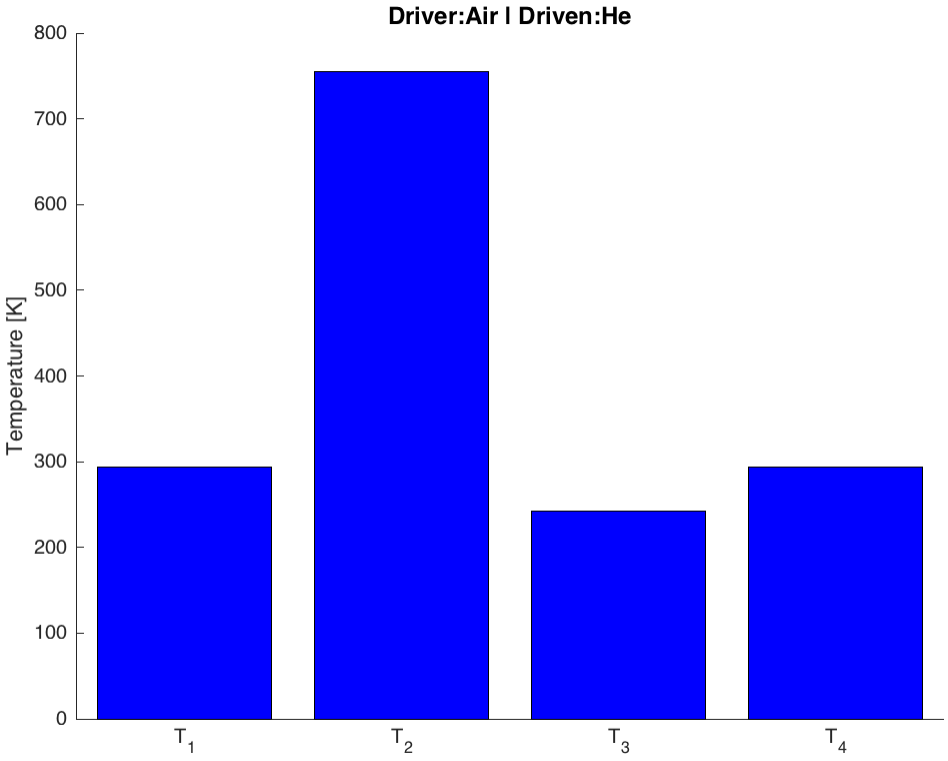

Driver:H2 I Driven:H2
×10-3
time [s]
x [m]
x12
x23
x34
x4

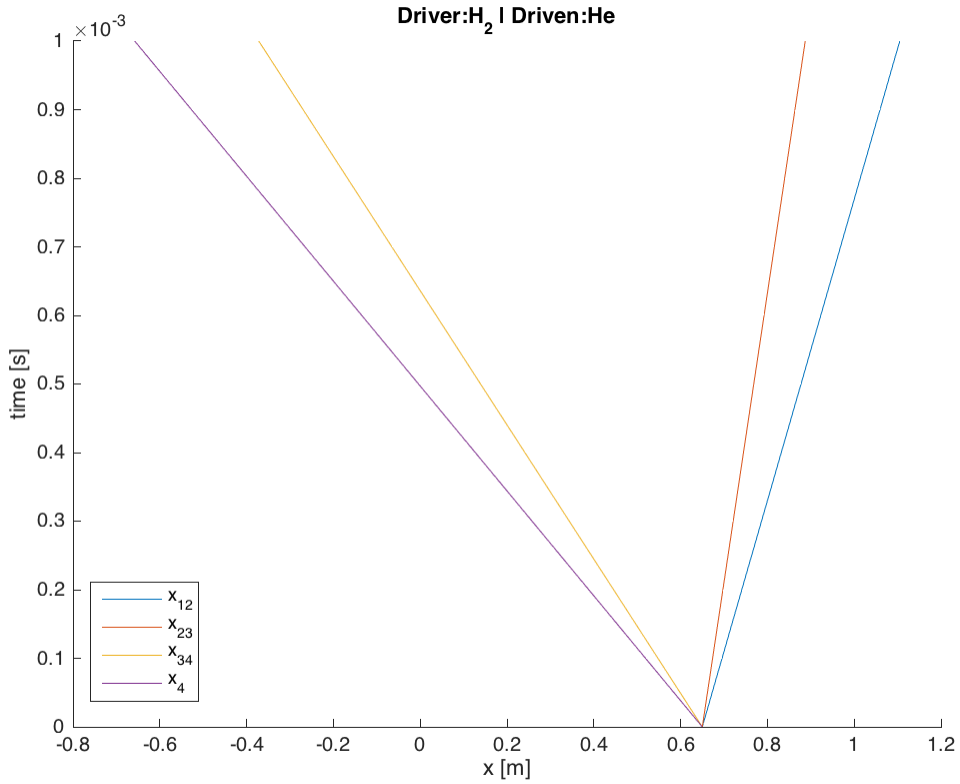

Driver:H2 I Driven:H2
Temperature [K]
T1
T2
T3
T4

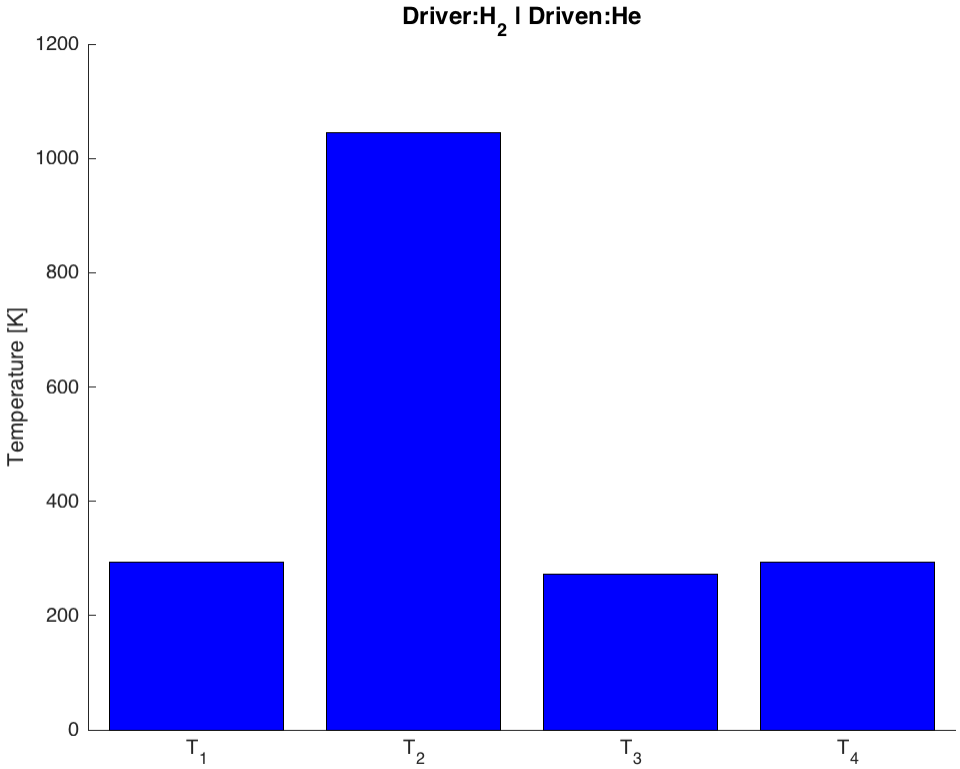

Driver:He I Driven:H2
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
x [m]
x12
x23
x34
x4

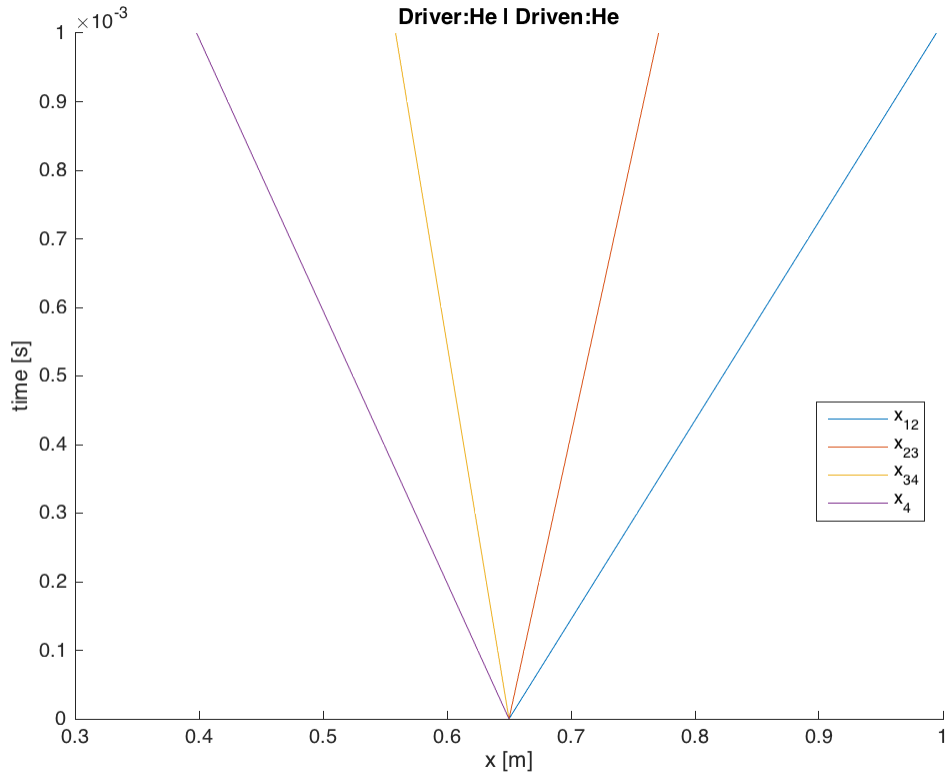

Driver:He I Driven:H2
500
450
400
350
300
250
200
150
100
50
0
Temperature [K]
T1
T2
T3
T4

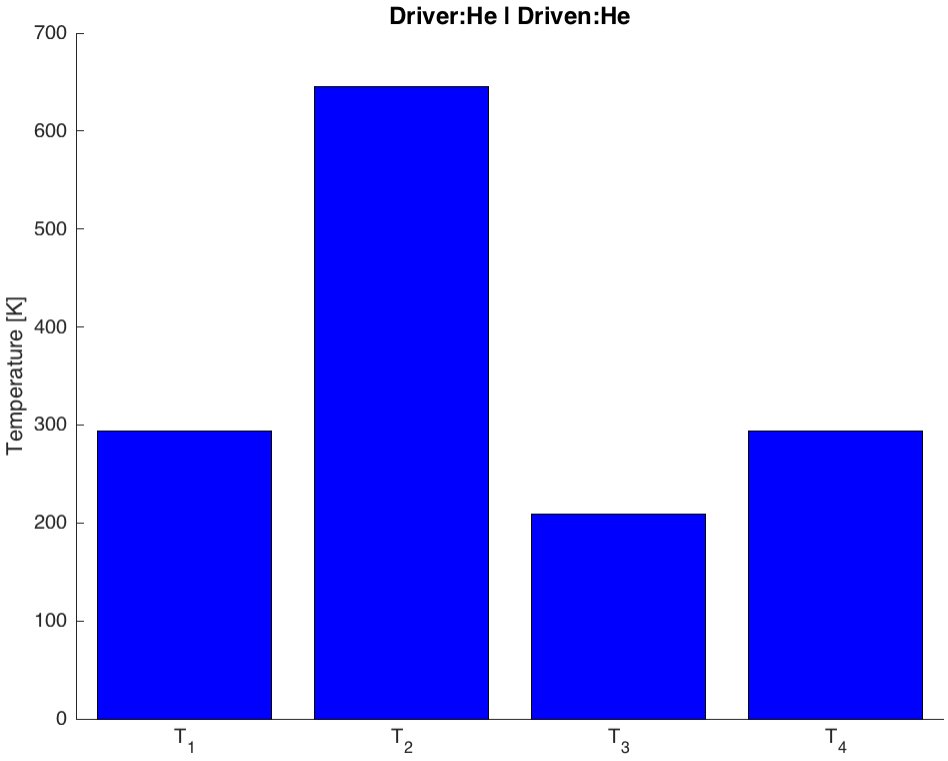

Driver:Air I Driven:He
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
x [m]
x12
x23
x34
x4

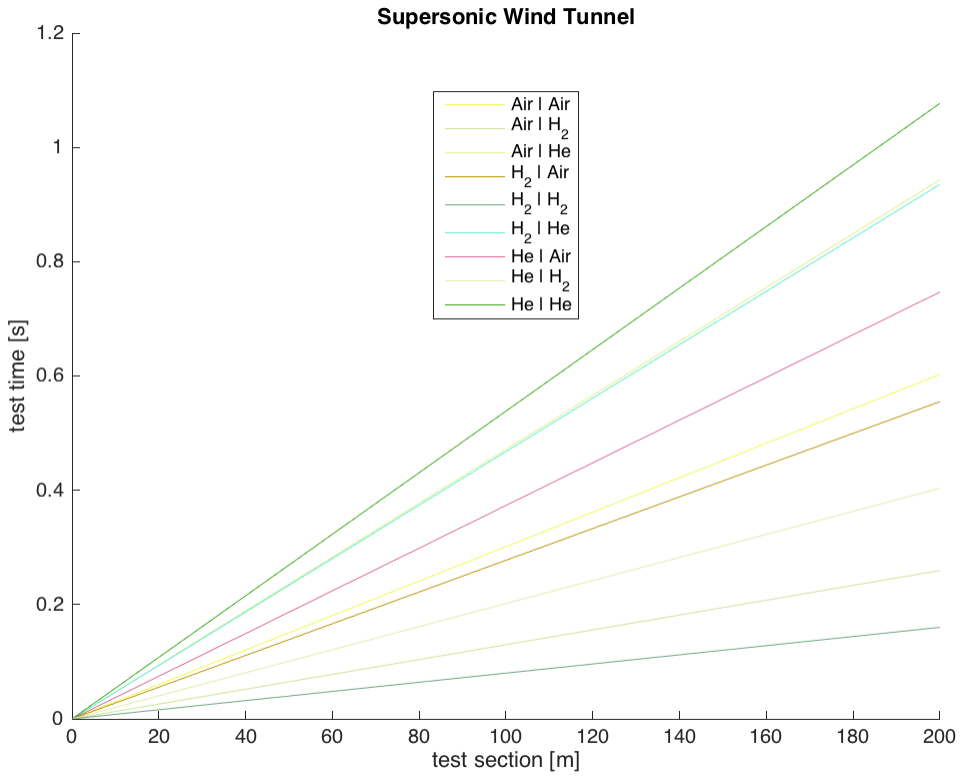

Driver:Air I Driven:He
800
700
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4

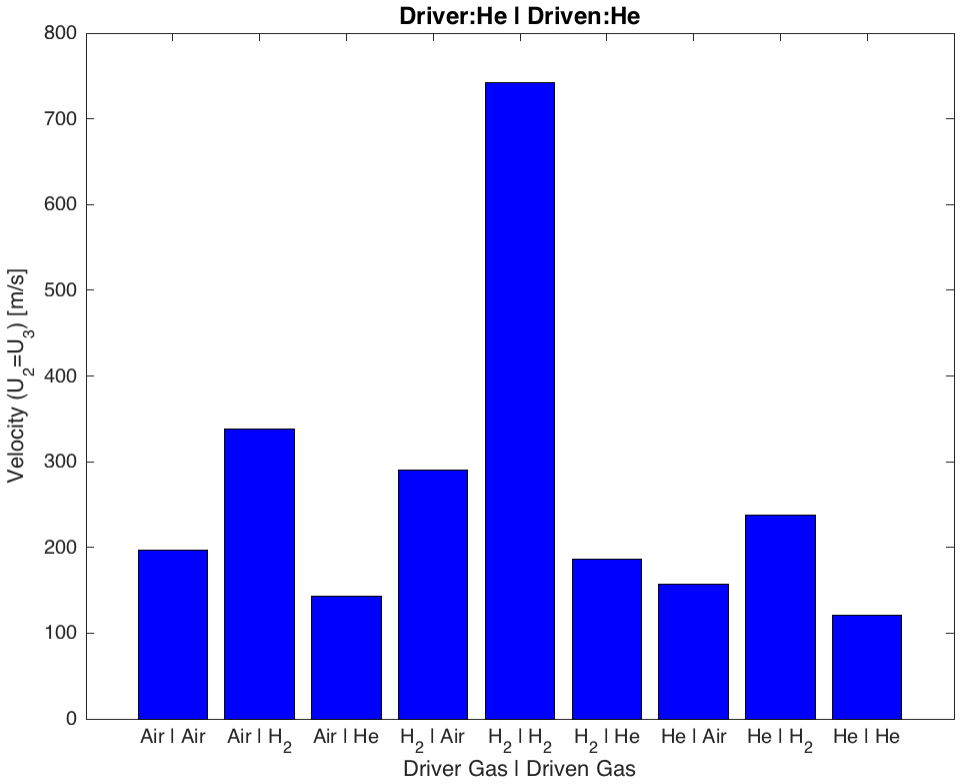

Driver:H2 I Driven:He
×10-3
time [s]
x [m]
x12
x23
x34
x4

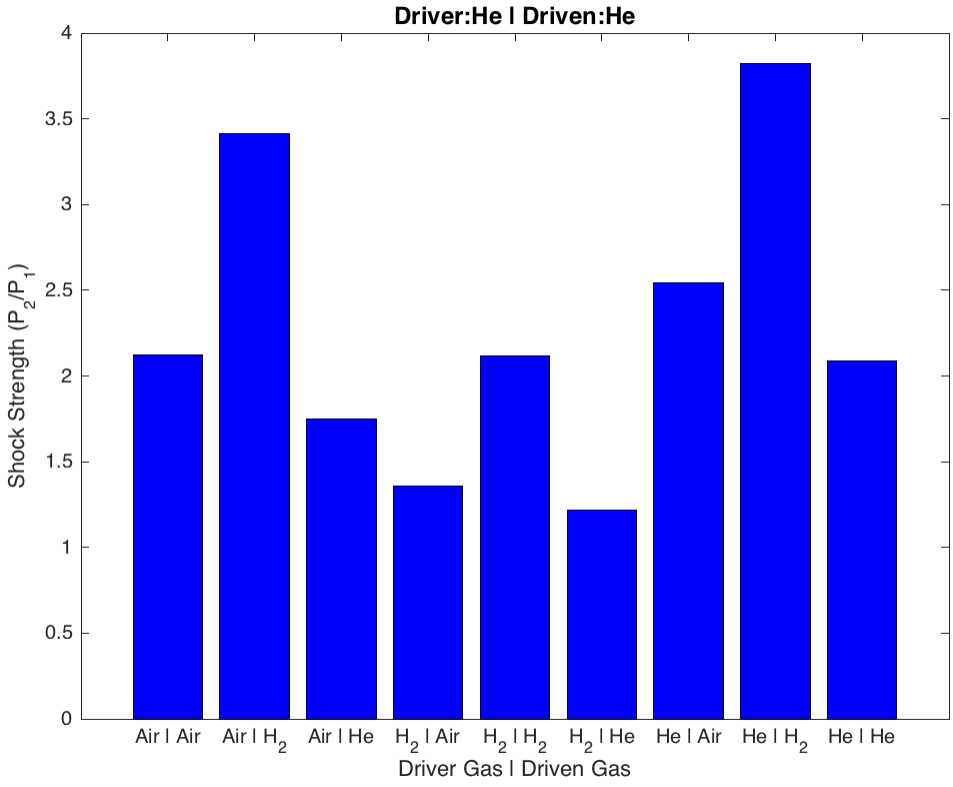

Driver:H2 I Driven:He
Temperature [K]
T1
T2
T3
T4

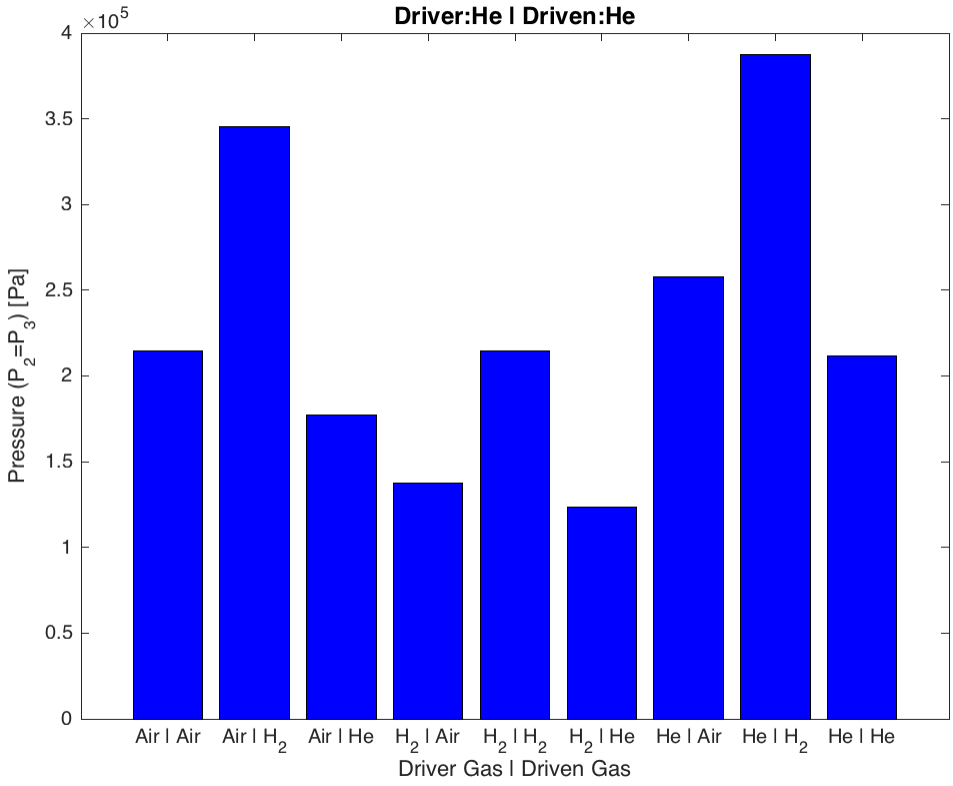

Driver:He I Driven:He
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x [m]
x12
x23
x34
x4


Driver:He I Driven:He
700
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4


Supersonic Wind Tunnel
test time [s]
test section [m]
Air I Air
Air I H2
Air I He
H2 I Air
H2 I H2
H2 I He
He I Air
He I H2
He I He


Driver:He I Driven:He
Velocity (U2=U3) [m/s]
Air I Air
Air I H2
Air I He
H2 I Air
H2 I H2
H2 I He
He I Air
He I H2
He I He
Driver Gas I Driven Gas


Driver:He I Driven:He
Shock Strength (P_2/P_1)
0
0.5
1
1.5
2
2.5
3
3.5
4
Air I Air
Air I H_2
Air I He
H_2 I Air
H_2 I H_2
H_2 I He
He I Air
He I H_2
He I He
Driver Gas I Driven Gas


Driver:He I Driven:He
$\times 10^5$
Pressure (P_2=P_3) [Pa]
0
0.5
1
1.5
2
2.5
3
3.5
4
Air I Air
Air I H_2
Air I He
H_2 I Air
H_2 I H_2
H_2 I He
He I Air
He I H_2
He I He
Driver Gas I Driven Gas

Effects of initial temperature on flow and strength

```
% intialization
T_1 = -100:100:100;
T_1 = T_1 + T_initial;
T_4 = -100:100:100;
T_4 = T_4 + T_initial;
count = 0;

U = [];
P = [];
P2_P1=[];
for i = 1:length(T_1)
    for j = 1:length(T_4)
        count = count + 1;
        % initial conditions and parameters
        gamma1 = gamma_Air;
        gamma4 = gamma_Air;
        R1 = R_Air;
        R4 = R_Air;
        T1 = T_1(i);
        T4 = T_4(j);

        % speed of sound

        a1 = sqrt(gamma1*R1*T1);
        a4 = sqrt(gamma4*R4*T4);

        %  shock strength
        fun = @nonlinfunc; x0 = 1; x = fsolve(fun,x0);
        p2_p1 = x;

        % other flow quantities
        p3_p4 = p2_p1/p4_p1;
        T3 = T4*(p3_p4)^((gamma4-1)/gamma4);
        T2 = T1*p2_p1*(((gamma1+1)/(gamma1-1)+p2_p1)/(1+(gamma1+1/
(gamma1-1)*p2_p1)));
        a3 = sqrt(gamma4*R4*T3);
        Ms = sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1);

        % velocities of interfaces
        up = (a1/gamma1)*(p2_p1-1)*(2*gamma1/(gamma1+1)/
(p2_p1+(gamma1-1)/(gamma1+1)))^0.5; % contact surface (driver/driven)
 speed
        W = a1*sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1); % shock speed
        u3 = up; % driven gas speed
        u_tail = up-a3; % tail of expansion wave speed
        u_head = -a4; % head of expansion wave speed

        % intialization
        x_12 = [];
```

```
        x_23 = [];
        x_34 = [];
        x_4 = [];

        t_experiment = [];
        for x = x_testsection
            t_experiment = [t_experiment,x/up - x/W];
        end

        for t = time

            % Shock wave location, contact surface, head and tail of
expansion
            x_12 = [x_12,W*t + membrane];
            x_23 = [x_23,up*t + membrane];
            x_34 = [x_34,u_tail*t + membrane];
            x_4 = [x_4,u_head*t + membrane];

        end
        figure, hold on
        set(gcf,'color','w');
        bar([T1,T2,T3,T4],'b')
        set(gca,'XTick',1:4,'XTickLabel',{'T_1','T_2','T_3','T_4'})
        title(strcat('T_1=',num2str(T_1(i)),'K |
T_4=',num2str(T_4(j)),'K'));%,'R=(',num2str(R_gases(j)),'); Driven =
',Labels(i),'R=(',num2str(R_gases(i)),')'))
        ylabel('Temperature [K]')

        U = [U,up];
        P = [P, p2_p1*p1];
        P2_P1 = [P2_P1, p2_p1];

        % figure
        figure, hold on
        set(gcf,'color','w');
        plot(x_12,time), hold on
        plot(x_23,time), hold on
        plot(x_34,time), hold on
        plot(x_4,time)
        legend('x_1_2','x_2_3','x_3_4','x_4','location','best')
        xlabel('x [m]');ylabel('time [s]')
        title(strcat('T_1=',num2str(T_1(i)),'K |
T_2=',num2str(T_4(j)),'K'))


        figure(56), hold on
        set(gcf,'color','w');
        plot(x_testsection,t_experiment,'color',[rand(1) rand(1)
rand(1)]), hold on
        xlabel('test section [m]'), hold on  % relative to membrane
        ylabel('test time [s]'), hold on
        title('Supersonic Wind Tunnel'), hold on
```

```
    end
end

figure(56), hold on
legend('T_1=193K | T_4=193K', 'T_1=193K | T_4=293K', 'T_1=193K |
 T_4=393K','T_1=293K | T_4=193K','T_1=293K | T_4=293K', 'T_1=293K |
 T_4=393K', 'T_1=393K | T_4=193K', 'T_1=393K | T_4=293K', 'T_1=393K |
 T_4=393K','location','best')


figure
set(gcf,'color','w');

bar(U,'b')
set(gca,'XTick',1:9,'XTickLabel',{'193|193', '193|293', '193|
393','293|193','293|293', '293|393', '393|193', '393|293', '393|
393'});
ylabel('Velocity (U_2=U_3) [m/s]')
xlabel('Driver Temperature [K] | Driven Temperature [K]')


figure
set(gcf,'color','w');

bar(P,'b')
set(gca,'XTick',1:9,'XTickLabel',{'193|193', '193|293', '193|
393','293|193','293|293', '293|393', '393|193', '393|293', '393|
393'});
ylabel('Pressure (P_2=P_3) [Pa]')
xlabel('Driver Temperature [K] | Driven Temperature [K]')

figure
set(gcf,'color','w');

bar(P2_P1,'b')
set(gca,'XTick',1:9,'XTickLabel',{'193|193', '193|293', '193|
393','293|193','293|293', '293|393', '393|193', '393|293', '393|
393'});
ylabel('Shock Strength (P_2/P_1)')
xlabel('Driver Temperature [K] | Driven Temperature [K]')



toc
```

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

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fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

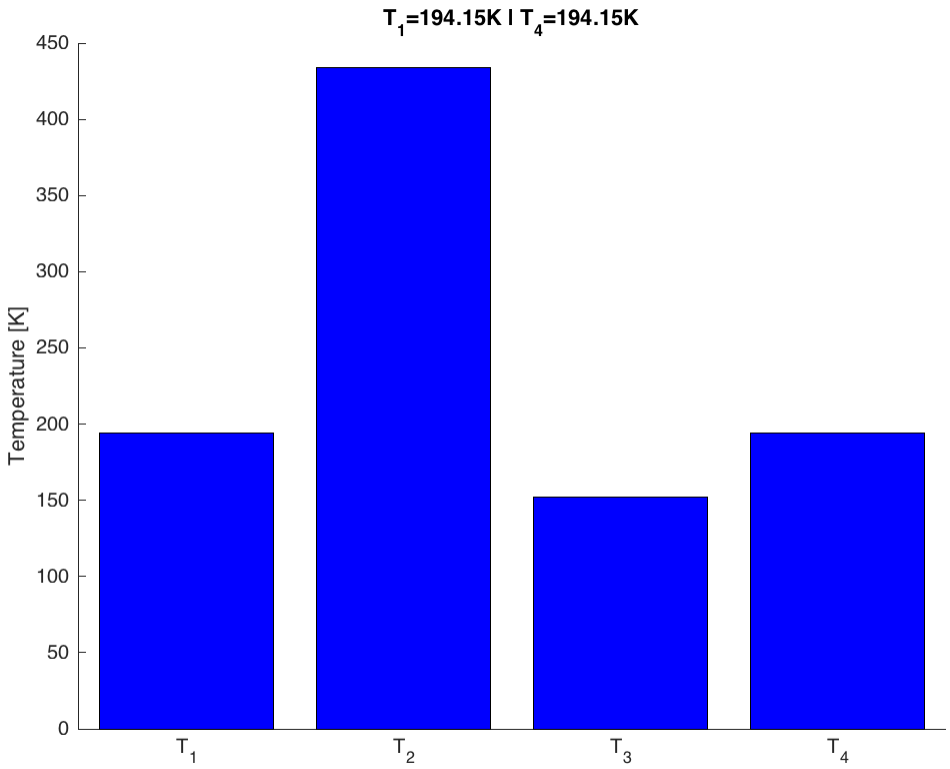
Equation solved.

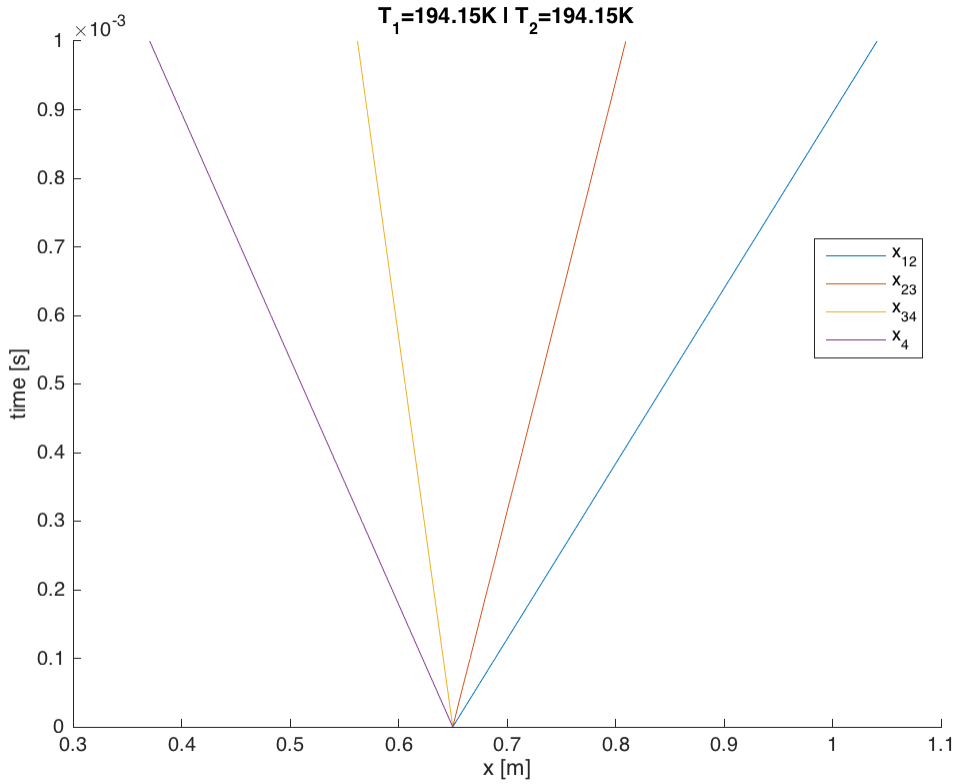
fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

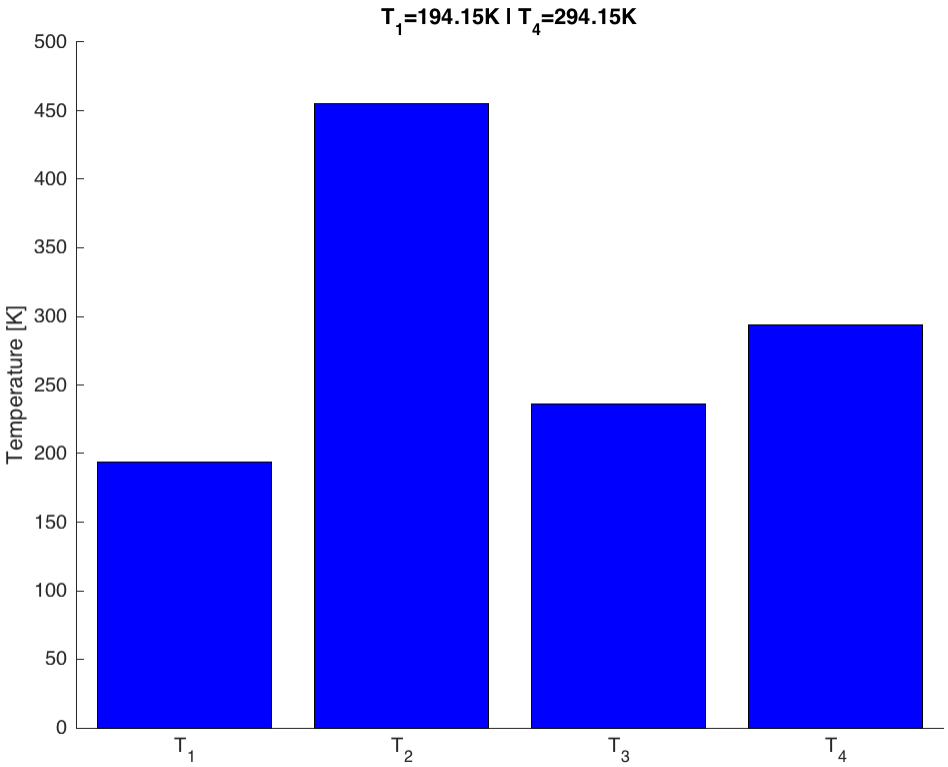
Equation solved.

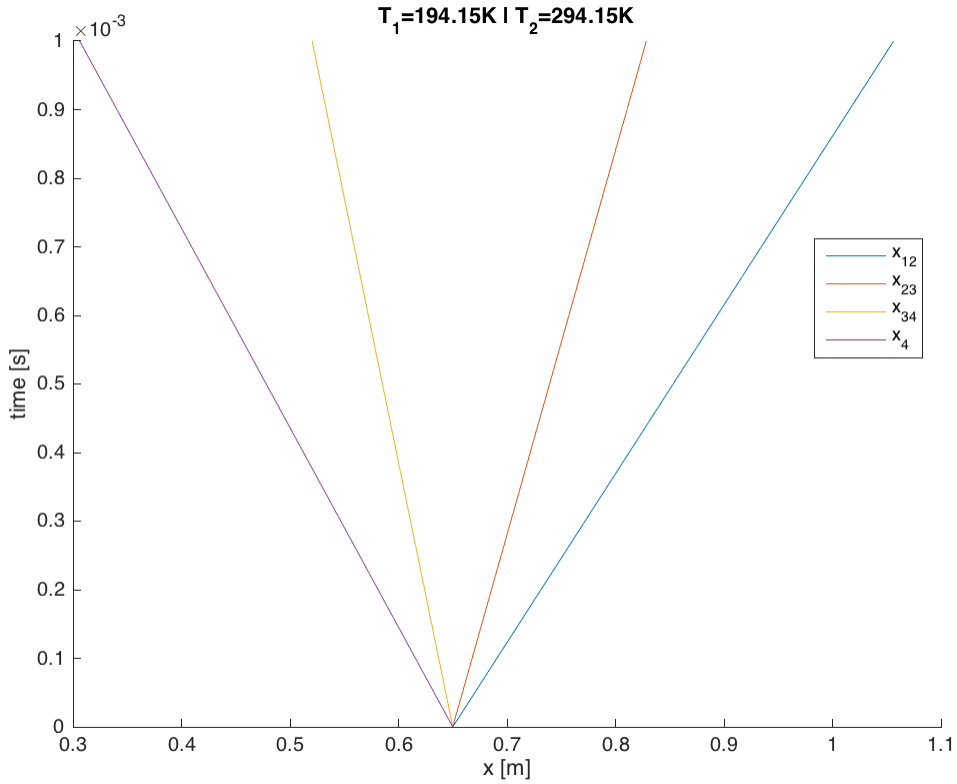
fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

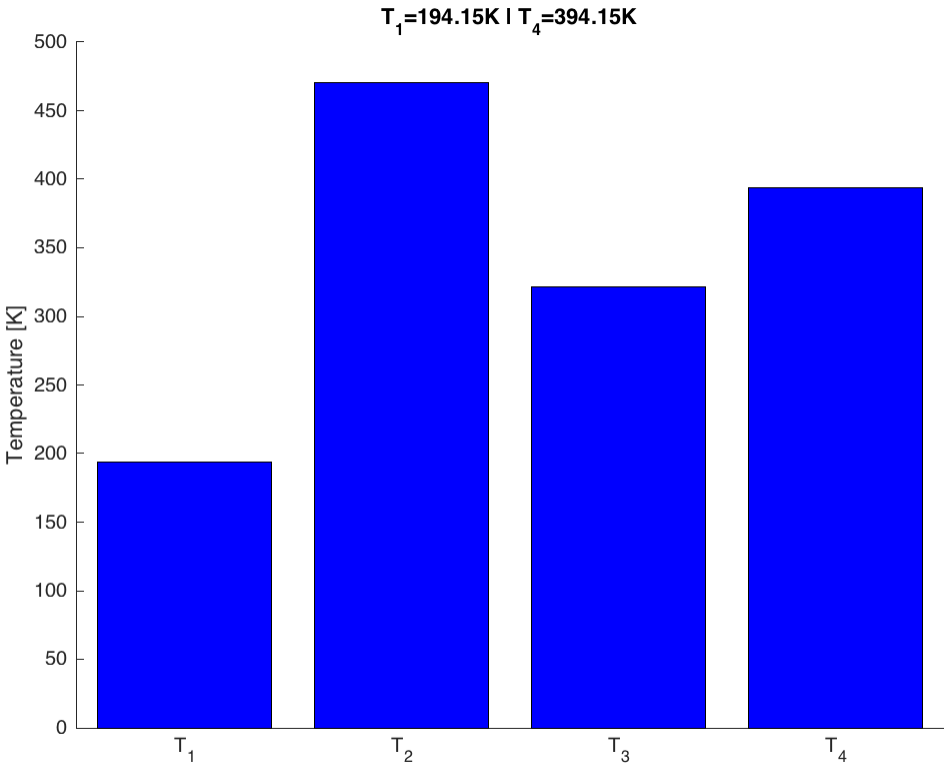
Elapsed time is 13.798132 seconds.

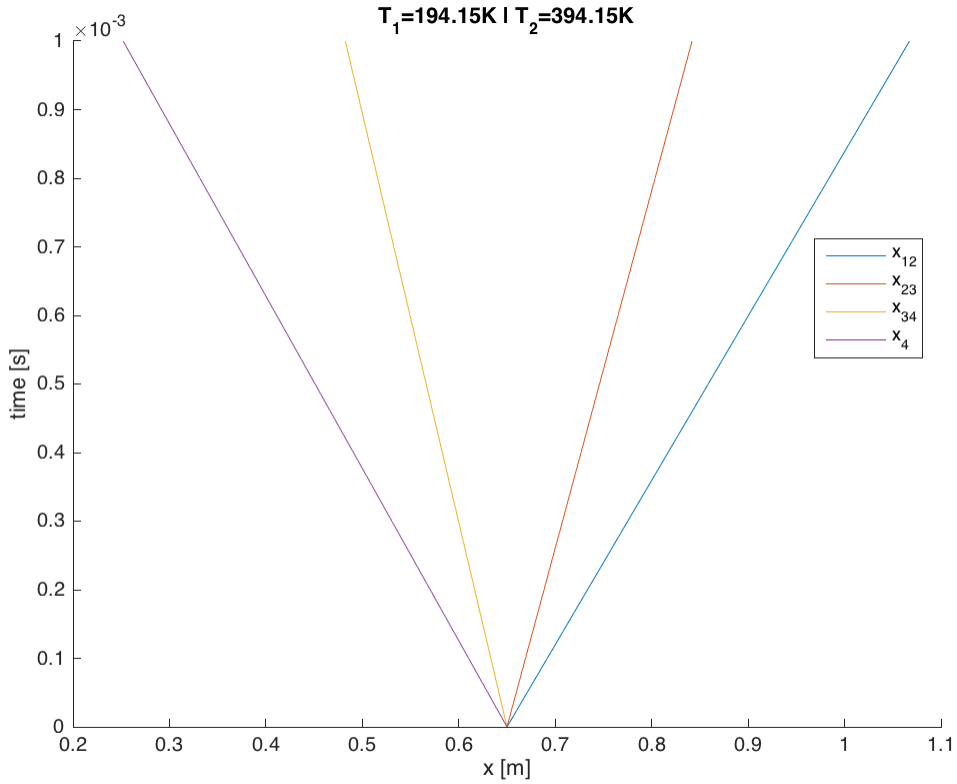


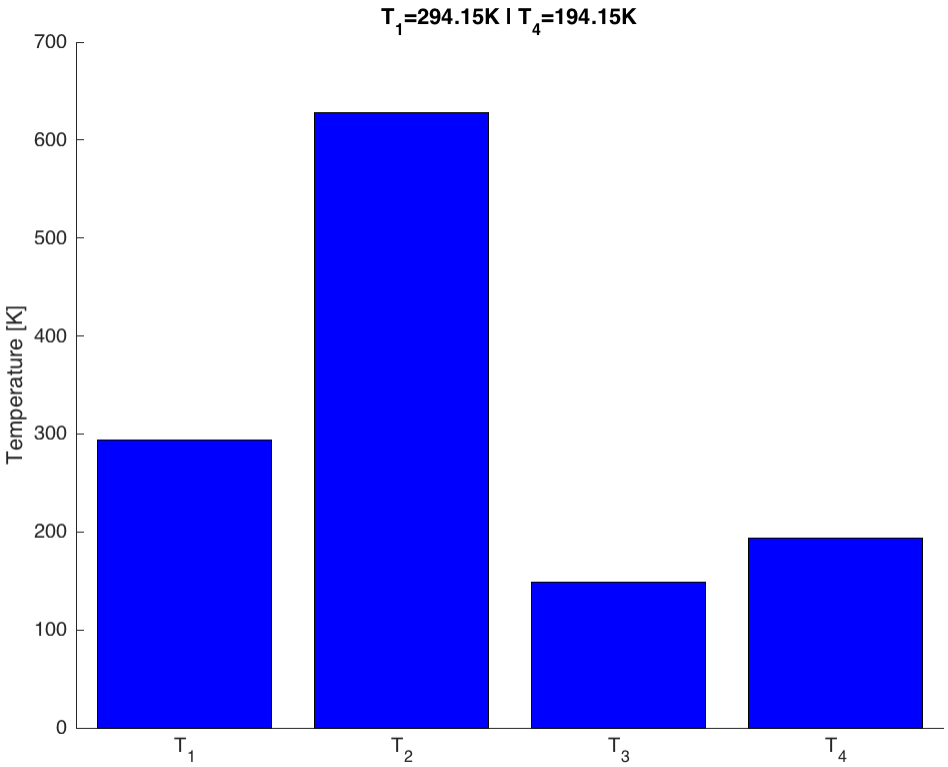

T1=194.15K I T2=194.15K
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
x [m]
x12
x23
x34
x4

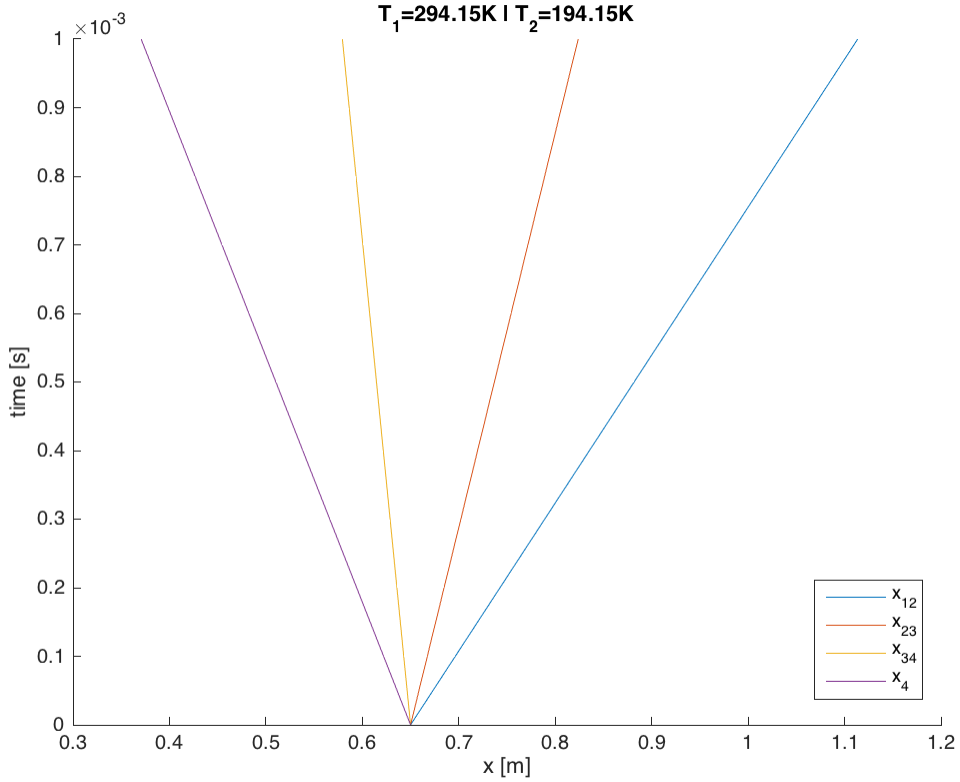

T1=194.15K I T4=294.15K
500
450
400
350
300
250
200
150
100
50
0
Temperature [K]
T1
T2
T3
T4

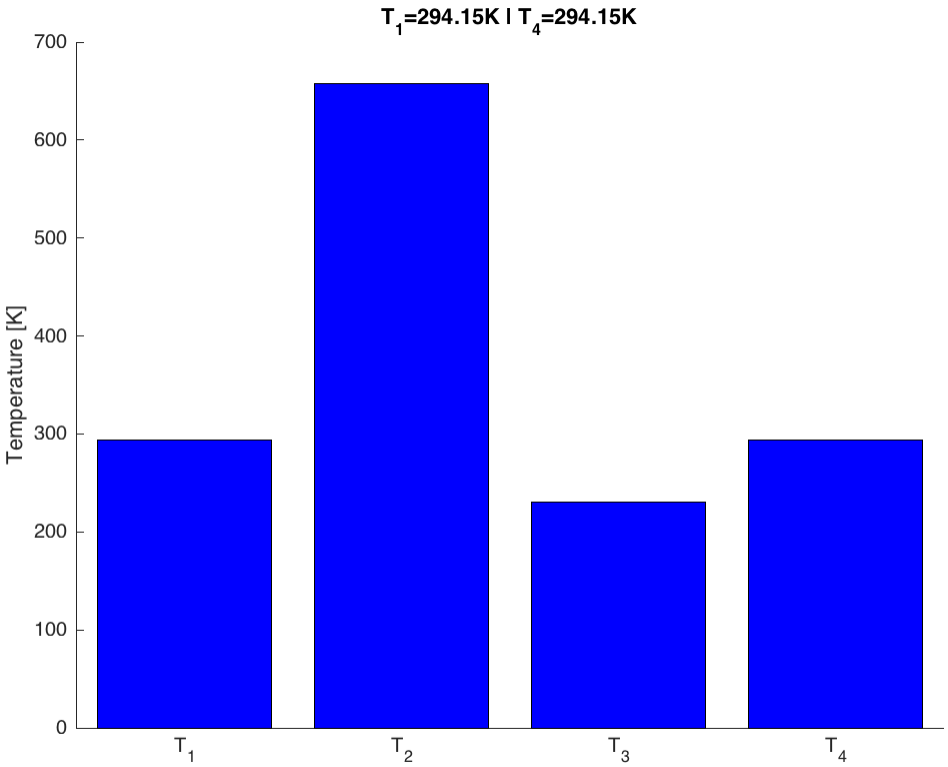

T1=194.15K I T2=294.15K
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
x [m]
x12
x23
x34
x4

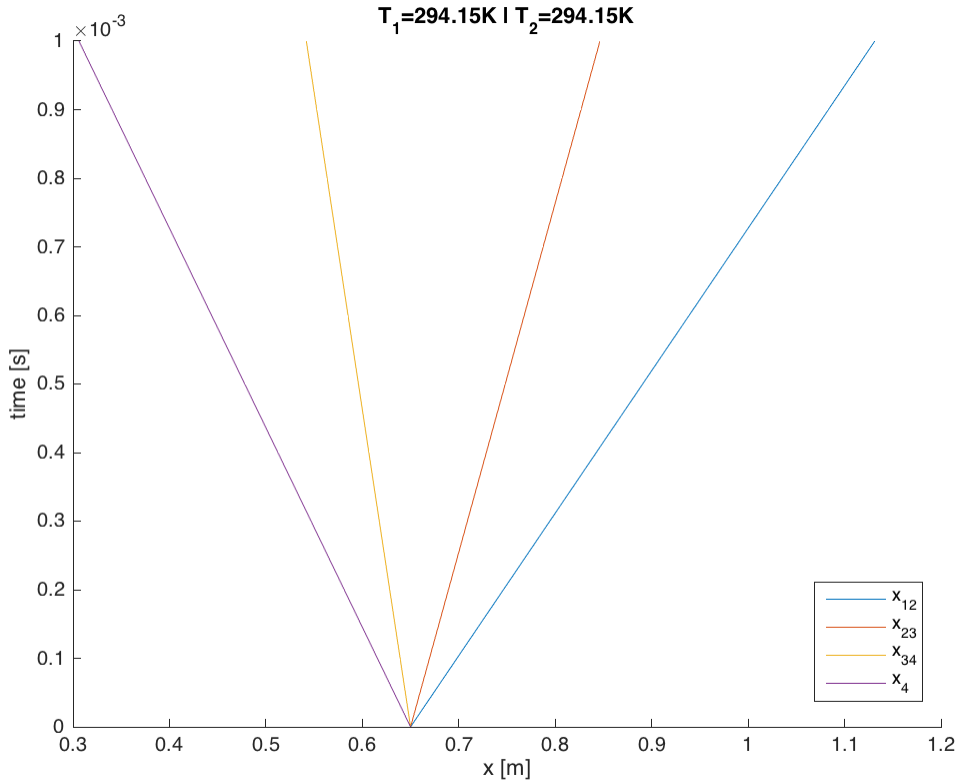

T1=194.15K I T4=394.15K
500
450
400
350
300
250
200
150
100
50
0
Temperature [K]
T1
T2
T3
T4

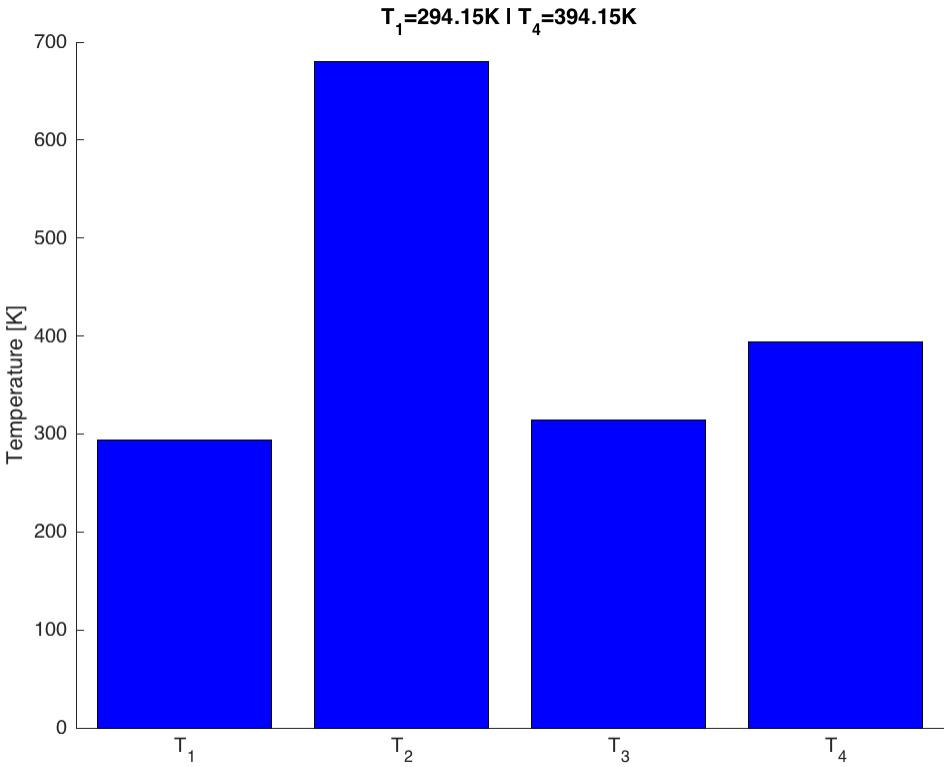

T1=194.15K I T2=394.15K
×10-3
time [s]
x [m]
x12
x23
x34
x4

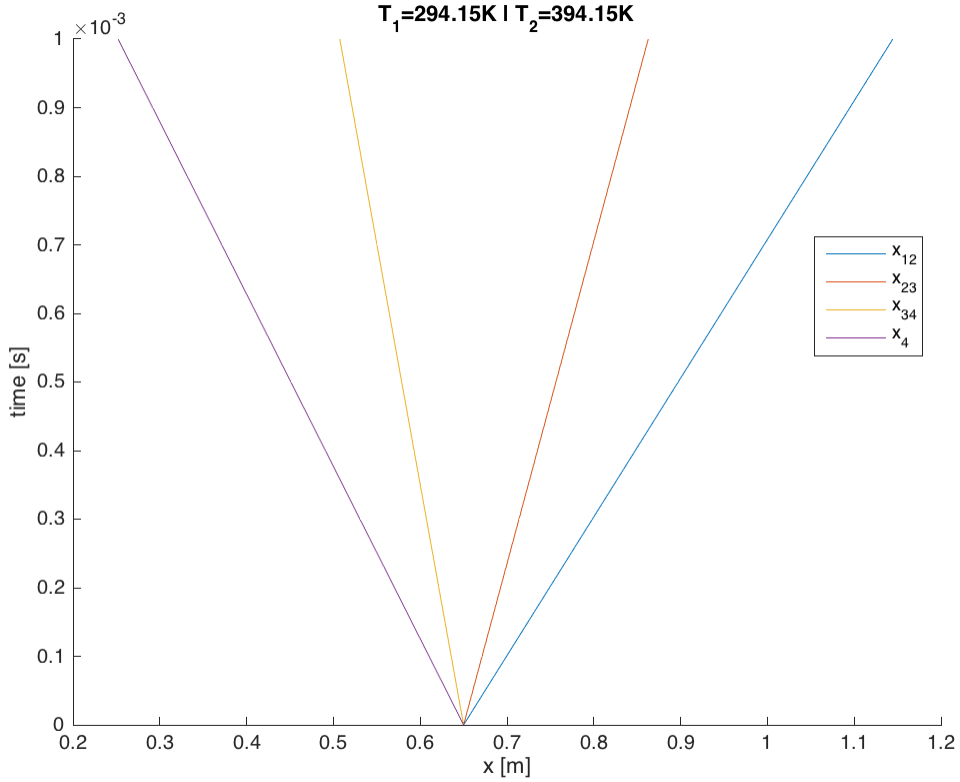

T1=294.15K I T4=194.15K
Temperature [K]
T1
T2
T3
T4

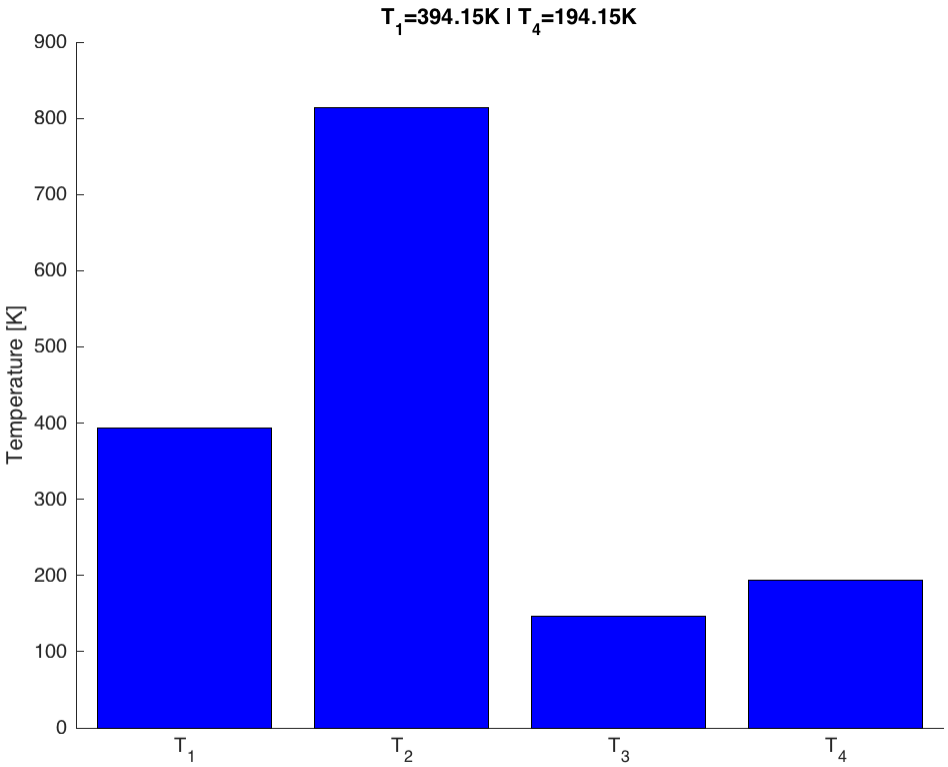

T1=294.15K I T2=194.15K
×10-3
time [s]
x [m]
x12
x23
x34
x4

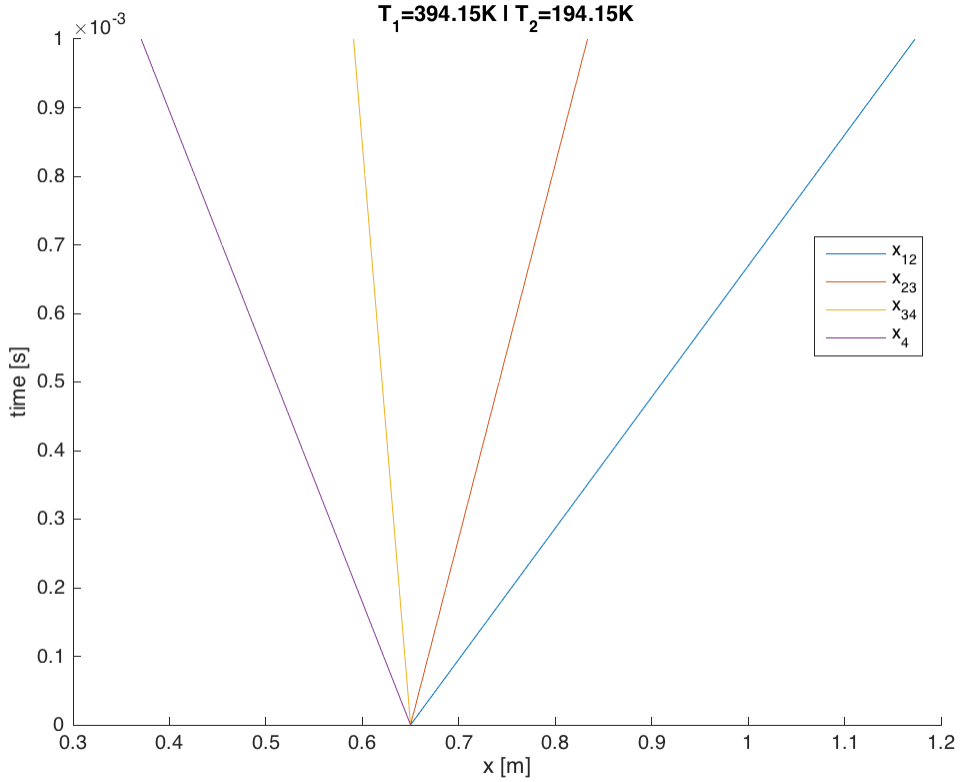

T1=294.15K I T4=294.15K
Temperature [K]
T1
T2
T3
T4

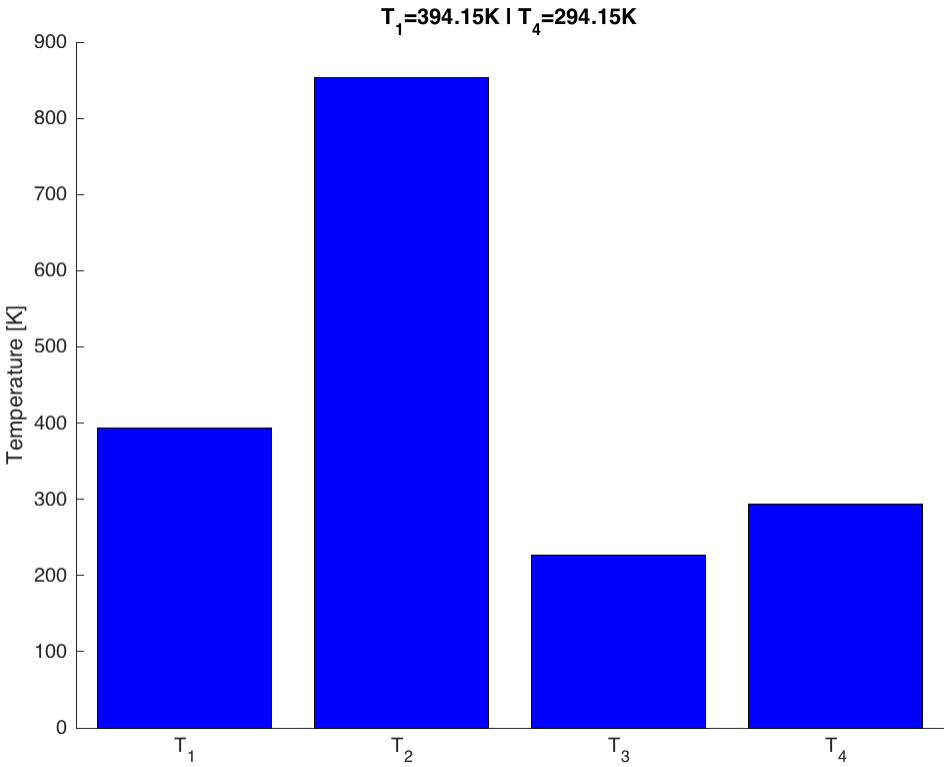

T1=294.15K I T2=294.15K
×10-3
time [s]
x [m]
x12
x23
x34
x4

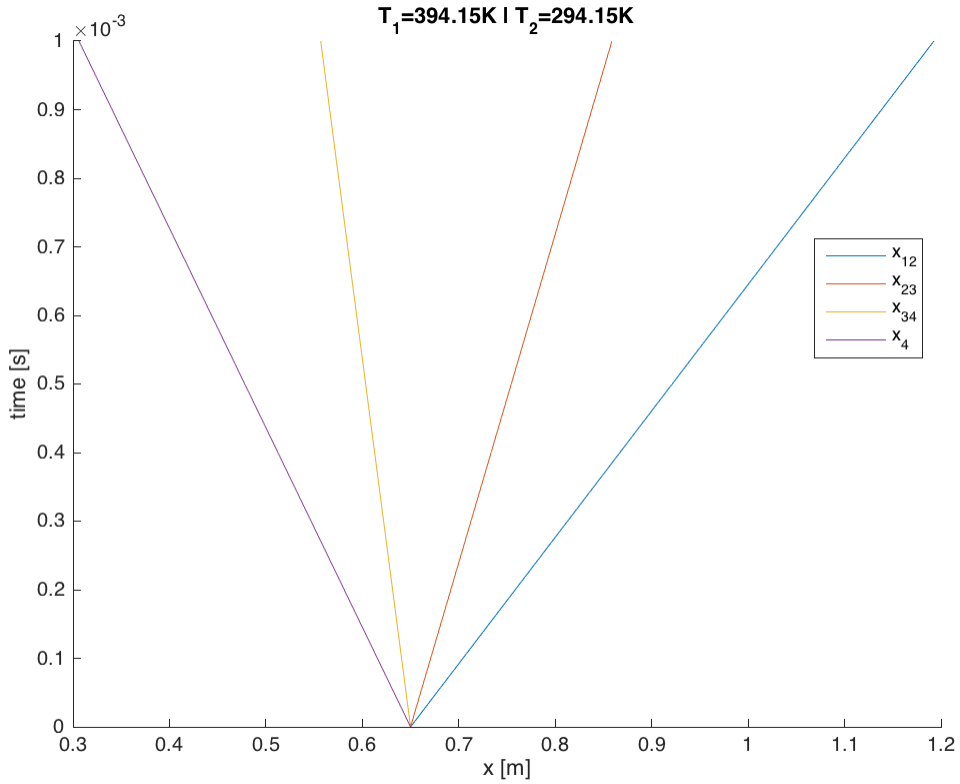

T1=294.15K I T4=394.15K
Temperature [K]
T1
T2
T3
T4

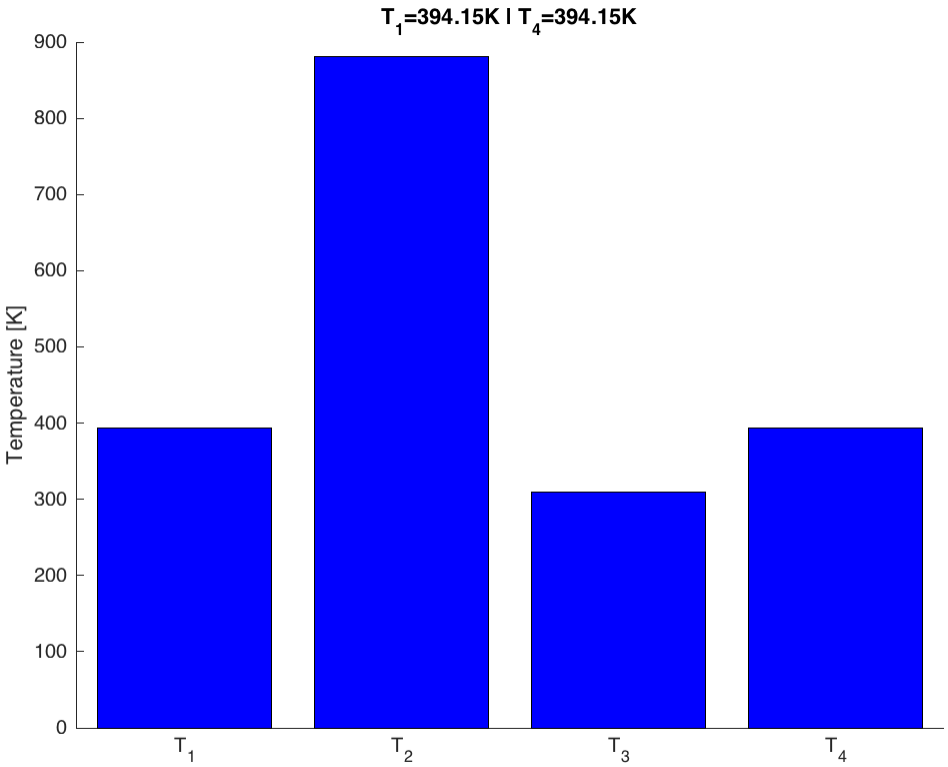

T1=294.15K I T2=394.15K
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
x [m]
x12
x23
x34
x4

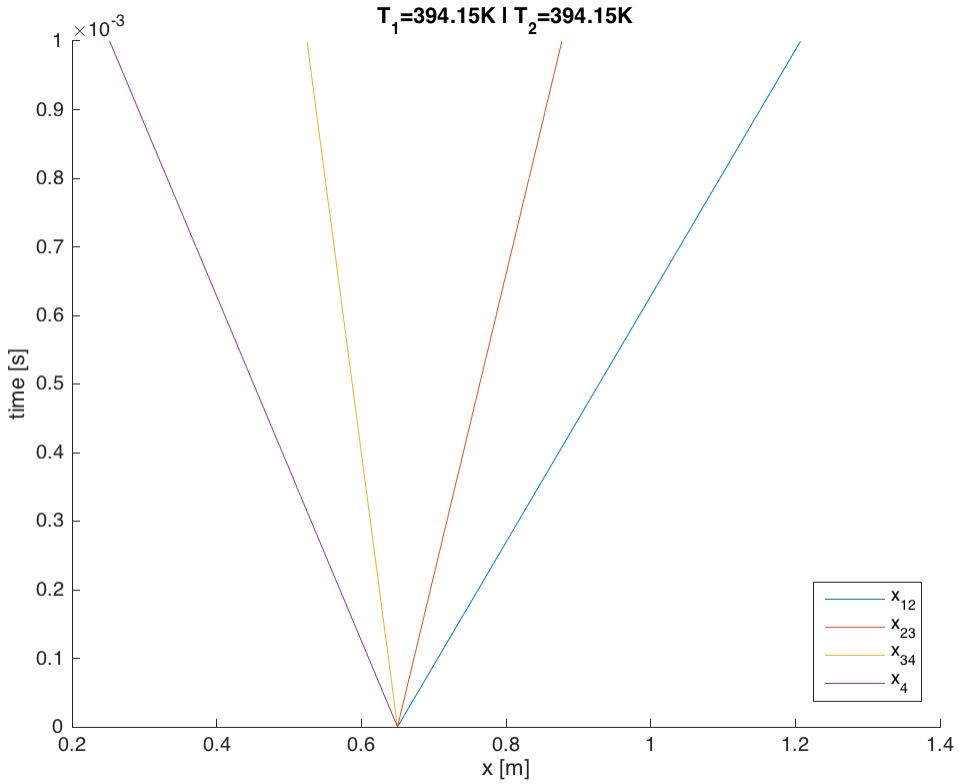

T1=394.15K I T4=194.15K
900
800
700
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4

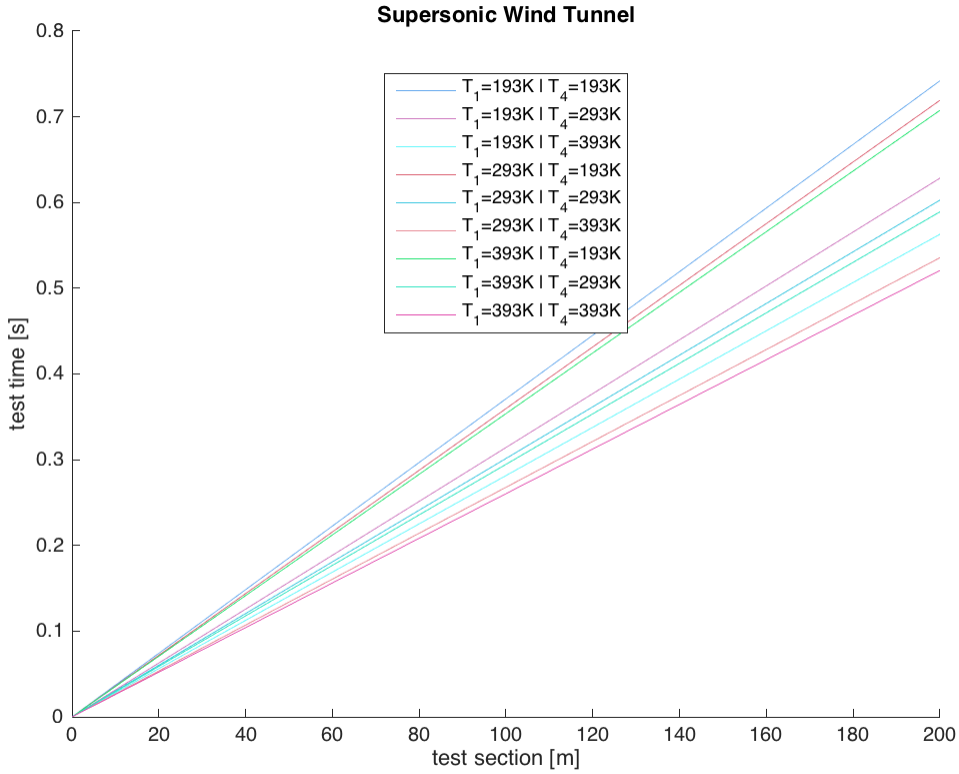

T1=394.15K I T2=194.15K
×10-3
time [s]
x [m]
x12
x23
x34
x4

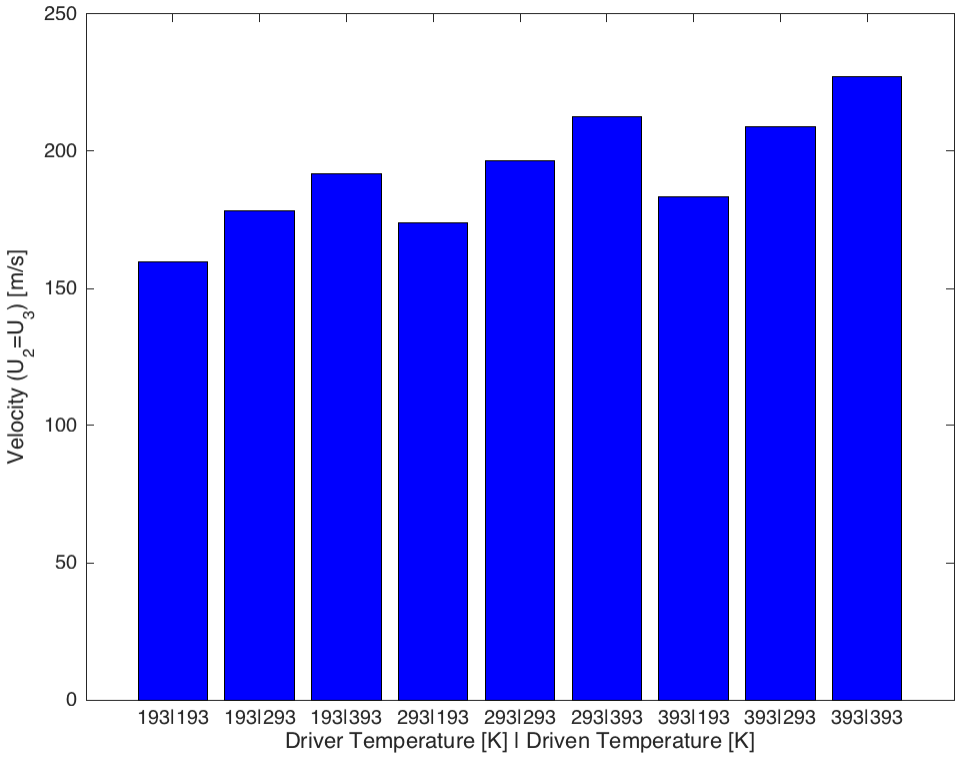

T1=394.15K I T4=294.15K
Temperature [K]
T1
T2
T3
T4

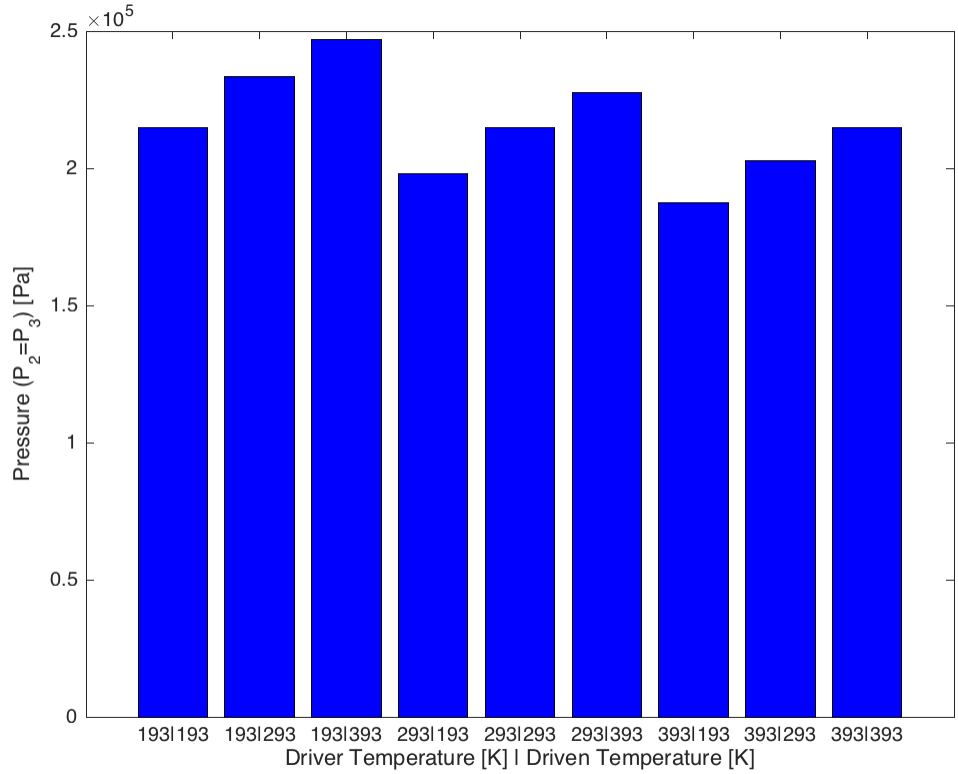

T1=394.15K I T2=294.15K
×10-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
time [s]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
x [m]
x12
x23
x34
x4

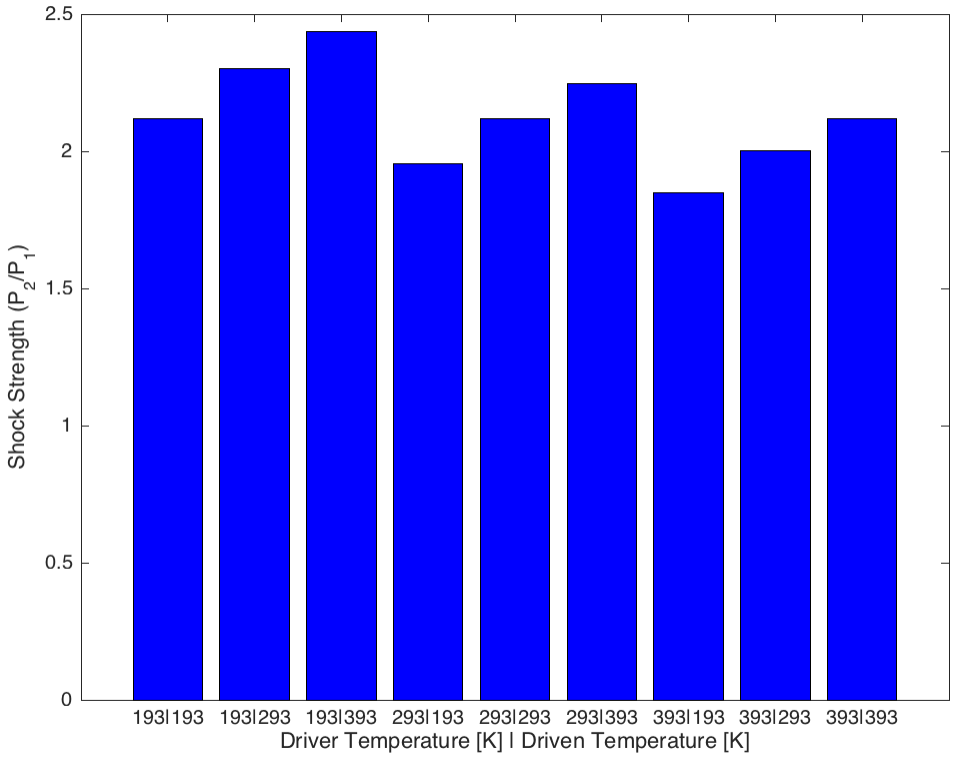

T1=394.15K I T4=394.15K
900
800
700
600
500
400
300
200
100
0
Temperature [K]
T1
T2
T3
T4


T1=394.15K I T2=394.15K
×10-3
time [s]
x [m]
x12
x23
x34
x4


Supersonic Wind Tunnel
test time [s]
test section [m]
T1=193K I T4=193K
T1=193K I T4=293K
T1=193K I T4=393K
T1=293K I T4=193K
T1=293K I T4=293K
T1=293K I T4=393K
T1=393K I T4=193K
T1=393K I T4=293K
T1=393K I T4=393K


250
200
150
100
50
0
Velocity (U_2=U_3) [m/s]
193|193
193|293
193|393
293|193
293|293
293|393
393|193
393|293
393|393
Driver Temperature [K] | Driven Temperature [K]


×10^5
2.5
2
1.5
1
0.5
0
Pressure (P_2=P_3) [Pa]
193|193
193|293
193|393
293|193
293|293
293|393
393|193
393|293
393|393
Driver Temperature [K] | Driven Temperature [K]



Reflected Shock Wave / Region 5

```
% initial conditions and parameters
R1 = R_Air;
R4 = R_Air;
gamma1 = gamma_Air;
gamma4 = gamma_Air;
T1 = T_initial;
T4 = T_initial;

% speed of sound
a1 = sqrt(gamma1*R1*T1);
a4 = sqrt(gamma4*R4*T4);

% shock strength
fun = @nonlinfunc; x0 = 1; x = fsolve(fun,x0);
p2_p1 = x;

% other flow quantities
p3_p4 = p2_p1/p4_p1;
T3 = T4*(p3_p4)^((gamma4-1)/gamma4);
a3 = sqrt(4*R4*T3);
Ms = sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1);
T2_T1 = (1+2*gamma1/(gamma1+1)*(Ms^2-1))*(2+(gamma1-1)*Ms^2)/
(gamma1+1)/Ms^2;
```

```
T2 = T2_T1*T1;
a2 = sqrt(gamma1*R1*T2);

% velocities of interfaces
up = (a1/gamma1)*(p2_p1-1)*(2*gamma1/(gamma1+1)/(p2_p1+(gamma1-1)/
(gamma1+1)))^0.5; % contact surface (driver/driven) speed
W = a1*sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1); % shock speed
u3 = up; % driven gas speed
u_tail = up-a3; % tail of expansion wave speed
u_head = -a4; % head of expansion wave speed

% reflected wave
fun = @nonlinfunc2; x0 = 2; x = fsolve(fun,x0);
Mr = x;

Wr = Mr*a2 - up;

p5_p2 = 1+ 2*gamma1/(gamma1+1)*(Mr^2-1);

p5 = p5_p2*p2_p1*p1;

rho5_rho2 = up/Wr;

T5_T2 = p5_p2/rho5_rho2;

T5 = T5_T2*T2_T1*T1;

%}
```

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Equation solved.

fsolve completed because the vector of function values is near zero as measured by the default value of the function tolerance, and the problem appears regular as measured by the gradient.

Method of Characteristics

```
% initial conditions and parameters
R1 = R_Air;
R4 = R_Air;
```

```
gamma1 = gamma_Air;
gamma4 = gamma_Air;
T1 = T_initial;
T4 = T_initial;

% speed of sound
a1 = sqrt(gamma1*R1*T1);
a4 = sqrt(gamma4*R4*T4);

% shock strength
fun = @nonlinfunc; x0 = 1; x = fsolve(fun,x0);
p2_p1 = x;

% other flow quantities
p3_p4 = p2_p1/p4_p1;
T3 = T4*(p3_p4)^((gamma4-1)/gamma4);
a3 = sqrt(4*R4*T3);
Ms = sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1);
T2_T1 = (1+2*gamma1/(gamma1+1)*(Ms^2-1))*(2+(gamma1-1)*Ms^2)/
(gamma1+1)/Ms^2;
T2 = T2_T1*T1;
a2 = sqrt(gamma1*R1*T2);

% velocities of interfaces
up = (a1/gamma1)*(p2_p1-1)*(2*gamma1/(gamma1+1)/(p2_p1+(gamma1-1)/
(gamma1+1)))^0.5; % contact surface (driver/driven) speed
W = a1*sqrt((gamma1+1)/2/gamma1*(p2_p1-1)+1); % shock speed
u3 = up; % driven gas speed
u_tail = up-a3; % tail of expansion wave speed
u_head = -a4; % head of expansion wave speed

% Time for Expansion Wave (head) reflection

t_wall = -membrane/-a4

% Velocity of contact surface

up

% Time for expansion wave to reflect off wall

t_reflect = membrane/a4



% Does expansion wave catch up with the shock wave before the shock
 wave reaches the right wall

% Expansion Wave / Non Simple Region


U1 = 0;
U4 = (2/(gamma4+1))*(a4+u3-a3);
U2 = -(U1-U4)/3+U1;
```

```
U3 = -(U1-U4)*2/3+U1;

A1 = a4;
A2 = a4*(1-(gamma4-1)/2*(U2/a4));
A3 = a4*(1-(gamma4-1)/2*(U3/a4));
A4 = a4*(1-(gamma4-1)/2*(U4/a4));

Jp1 = 2*a4/(gamma4-1);
Jm1 = -Jp1;
X1 = -A1*t_wall+membrane;

Jp2 = Jp1;
Jm2 = 2*U2-Jp2;
dxdt12 = (tan(0.5*(atan(1/(U1+A1))+atan(1/(U2+A2)))))^-1;
tol = 0.00001;
err = 5;
dt = 0.00000001;
t = 0;
t_mark = 0;
t1 = t_wall;
while err > tol
    t = t + dt;
    err = abs(abs(((t_wall+t)*(U2-A2) + membrane)-abs(t*dxdt12)));
end
t_mark = t_mark + t;
X2 = t*dxdt12 + X1;
t2 = t1+t_mark;


Jp3 = Jp1;
Jm3 = 2*U3-Jp3;
dxdt23 = (tan(0.5*(atan(1/(U2+A2))+atan(1/(U3+A3)))))^-1;
tol = 0.00001;
err = 5;
dt = 0.00000001;
t = 0;
while err > tol
    t = t + dt;
    err = abs(abs(((t+t_mark+t_wall)*(U3-A3) + membrane)) -
(abs(X2+t*dxdt23)));
end
t_mark = t_mark + t;
X3 = X2 + t*dxdt23;
t3 = t1+t_mark;


Jp4 = Jp1;
Jm4 = 2*U3-Jp4;
dxdt34 = (tan(0.5*(atan(1/(U3+A3))+atan(1/(U4+A4)))))^-1;
tol = 0.00001;
err = 5;
dt = 0.00000001;
t = 0;
while err > tol
```

```
    t = t + dt;
    err = abs(abs(((t+t_mark+t_wall)*(U4-A4) + membrane)) -
(abs(X3+t*dxdt34)));
end
t_mark = t_mark + t;
X4 = X3 + t*dxdt34;
t4 = t1 + t_mark;




Jp5 = -Jm2;
Jm5 = Jm2;
A5 = (gamma4-1)*Jp5/2;
U5 = 0;
X5 = 0;
dxdt25 = (tan(0.5*(atan(1/(U2-A2))+atan(1/(U5-A5)))))^-1;
dt5 = -X2/dxdt25;

Jp6 = Jp5;
Jm6 = Jm3;
U6 = 0.5*(Jp6+Jm6);
A6 = (gamma4-1)/4*(Jp6-Jm6);

dxdt56 = (tan(0.5*(atan(1/(U5+A5))+atan(1/(U6+A6)))))^-1;

dxdt36 = (tan(0.5*(atan(1/(U3-A3))+atan(1/(U6-A6)))))^-1;
tol = 0.0001;
t5 = t2 + dt5;
for x = X5:0.00001:X3
    abs((t5+x/dxdt56)+(t3+x/dxdt36));
    if abs((t5+x/dxdt56)+(t3+x/dxdt36)) < tol
        t6 = t5+x/dxdt56
        break
    end
end



% time for expansion wave to reach wall
expansion_time = t4+(wall-X4)/(0.5*(Jp4+Jm4)+u3)
% time for shock to reach wall
shock_time = (wall-membrane)/W



% u_incident = (tan(0.5*(atan(1/(u-a))+atan(1/(u-a)))))^-1;
%
% u_reflected = (tan(0.5*(atan(1/(u+a))+atan(1/(u+a)))))^-1;


Equation solved.
```

```
fsolve completed because the vector of function values is near zero
as measured by the default value of the function tolerance, and
the problem appears regular as measured by the gradient.



t_wall =

    0.0019


up =

  196.4041


t_reflect =

    0.0019


expansion_time =

    0.0175


shock_time =

    0.0055
```

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