ASE 4343 Project 2: Nozzle Analysis

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This report compares the experimental and computational data of flow run in converging nozzles and convergent-divergent nozzles at different inlet pressures.

Nomenclature

C	=	convergent
CD	=	convergent-divergent
M	=	Mach number
MFP	=	Mass Flow Parameter
p	=	static pressure
p_0	=	total pressure

I. Introduction

A nozzle is a tube of varying cross-sectional area that increases the speed of an outflow by controlling its direction and shape. Understanding the behavior of the flow in a nozzle is important for an aerospace engineer: from plane engines to rockets nozzles, they use the same principle to achieve propulsion. The concept exploited by the nozzle is the conversion of thermal energy of a flow to kinetic energy. The isentropic model of the nozzle is sufficient to decently simulate the nozzle flow. Two types of nozzles are studied here: convergent nozzle and convergent-divergent nozzle. Convergent nozzles do not deal with supersonic flows, and therefore the flow coming out of the nozzle can never be greater than 1. CD nozzles, on the other hand, is converging towards the throat and diverging behind it. Supersonic speed can be achived in the latter type of nozzles. ANSYS allows the simulation of flow in such types of nozzles. Comparison of computational and experimental results is therefore made possible.

II. C Nozzle

Experimentally, the static pressure and total pressure ratio p/p_0 is constant until a normalized distance of around 0.85 is reached, as shown in figure 1. The ratio then starts to drop at that point, when the speed of the flow starts to increase considerably. Indeed, when the velocity increases, static pressure drops, and as total pressure stays constant, the ratio decreases. Also, the higher the pressure at the inlet is, the earlier the pressure ratio starts to drop. As the flow at the inlet increases, the flow reaches its maximum speed at a point closer to the inlet.

Looking at the computational results, the pressure ratio does not stay constant, in contrast to the experimental data: it starts dropping right form the inlet and drops at a higher rate as it reaches around a normalized distance of 0.85.

The difference here might be due to the smoothly rounded walls of the actual converging nozzle. While the nozzle simulated on ANSYS has straight walls, the experimental nozzle has rounded walls, which allows a better transition to sonic speeds. This claim is confirmed by the abrupt drop in pressure ratio at 0.85 normalized distance.

* Aerospace Engineering Senior

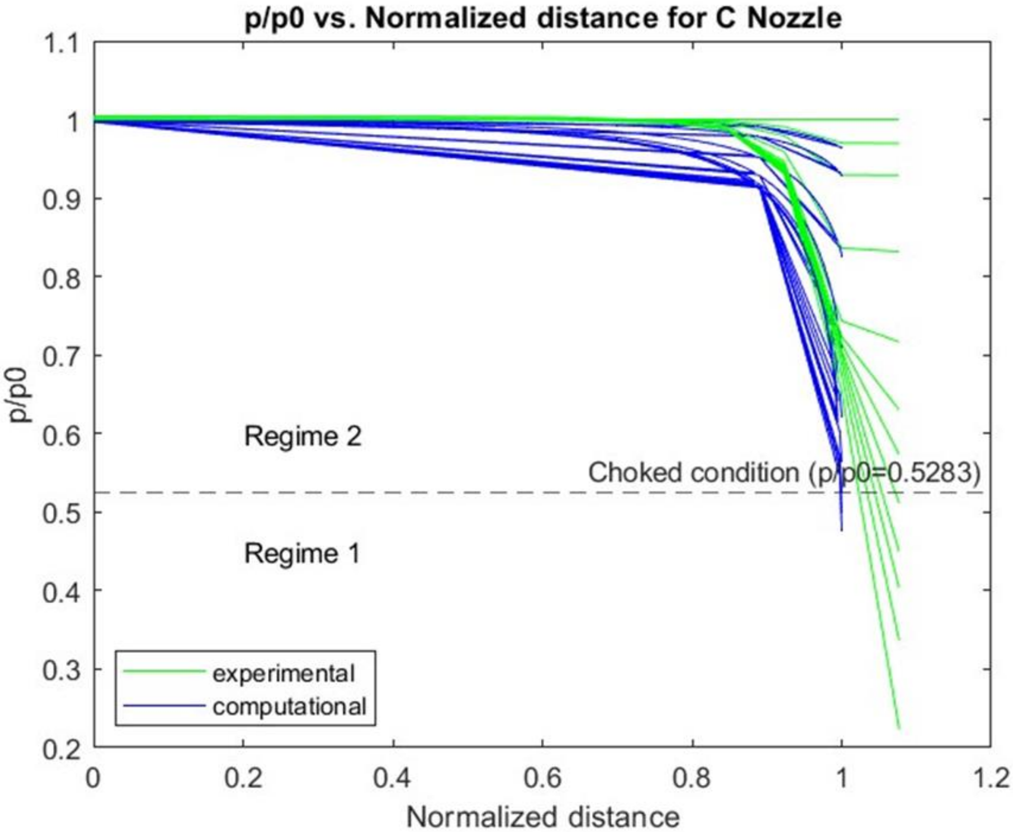

Figure 1: Plot representing p/p_0 vs. normalized distance for a C nozzle

Figure 2 reflects what was mentioned for figure 1: as the flow reaches a normalized distance of 0.85, the Mach number increases abruptly, as the pressure ratio decreases abruptly. In general, the computationally simulated reaches a higher Mach number than the experimentally simulated flow: as inviscid flow has been simulated on ANSYS, walls friction has been neglected. The computational flow therefore tends to be faster than the experimental flow.

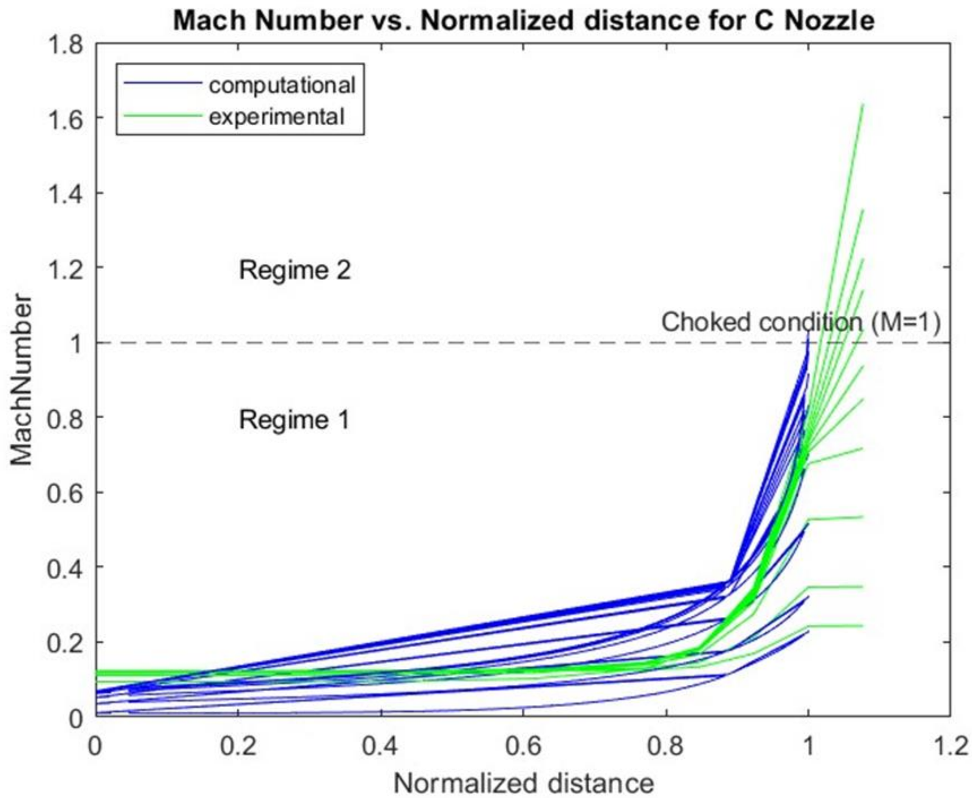

Figure 2: Plot representing Mach Number vs. Normalized distance for a C nozzle

As maximum speed is achieved at choked flow condition, the MFP is maximal because of the maximum mass flow. As p_B gets closer to p_0, MFP ends up dropping because the velocity drops: looking at the principle of a nozzle, if the back pressure is close to the inlet pressure, there is less likely to be air flowing from the inlet to the outlet of the nozzle.

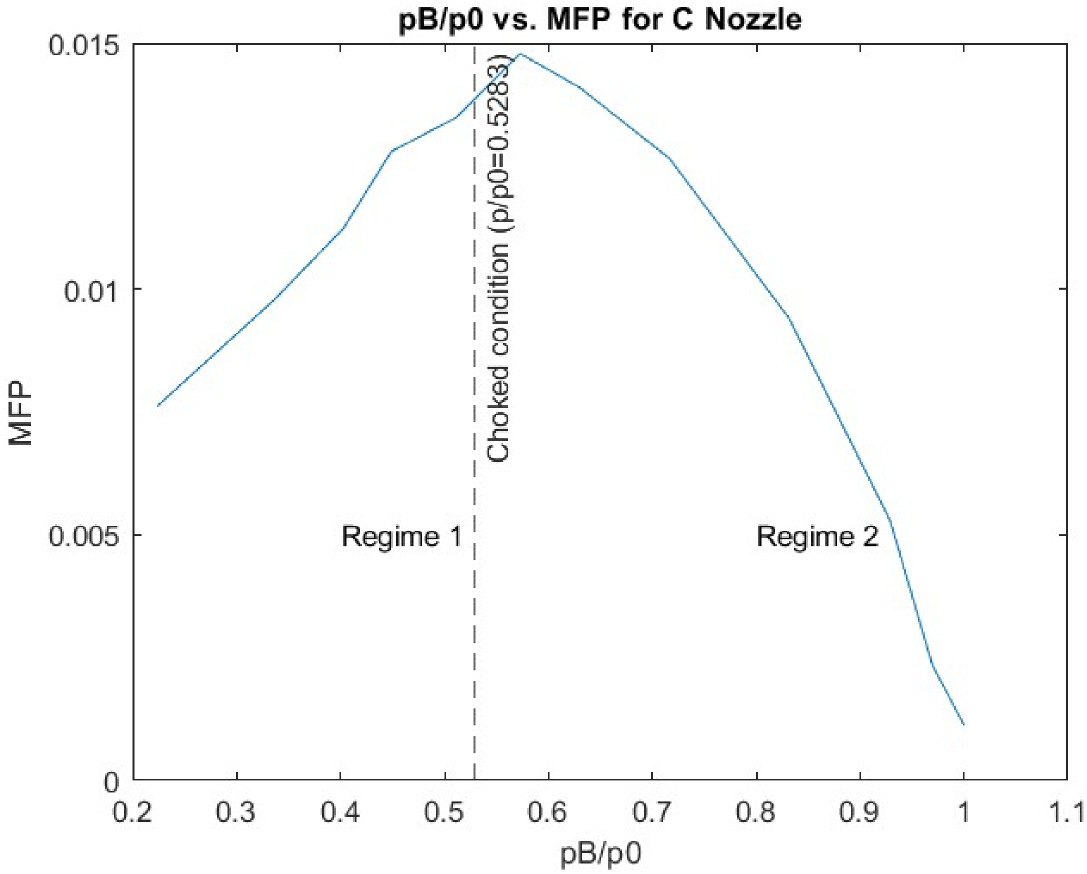

Figure 3: Plot representing MFP vs. p_B/p_0 for C nozzle

The area for each pressure value in the contour in figure 4 keeps decreasing as the inlet pressure increases. This represents a faster pressure drop. As represented in figures 1 and 2, the higher the static pressure at the inlet is, the fastest the pressure drop is, and the higher the Mach number increases. Indeed, in figure 2, the slope of the Mach number increases as the pressure at the inlet increases. In the Mach number contour plots, the transition line in between the different Mach numbers (dark blue and sky blue) gets closer to the inlet. This means that the transition to sonic spped happens further to the inlet. The pressure is maintained over a longer distance than for a lower static inlet pressure. As the pressure increases at the inlet, the velocity is high, and the mass flow is maintained, and it is not until the cross-sectional area becomes small enough that the speed changes, and therefore that the pressure drops.

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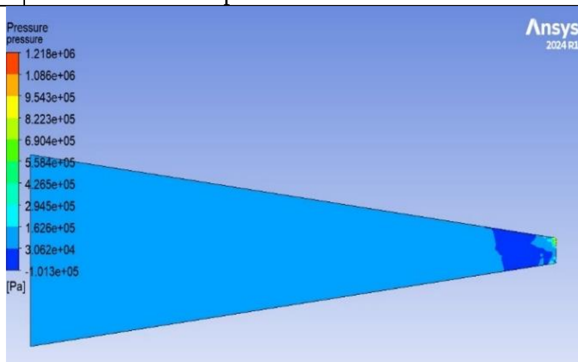
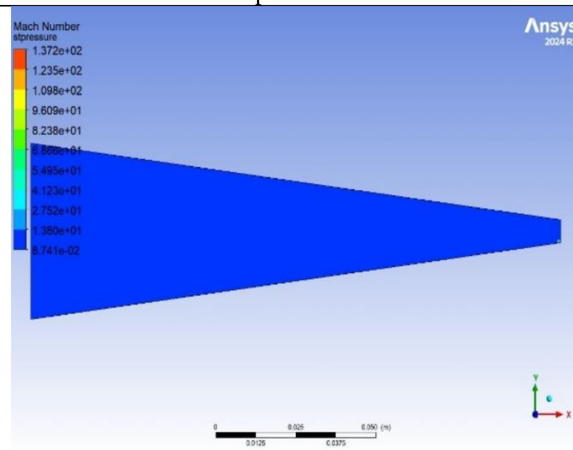
<tr><td>1</td><td>
</td><td>
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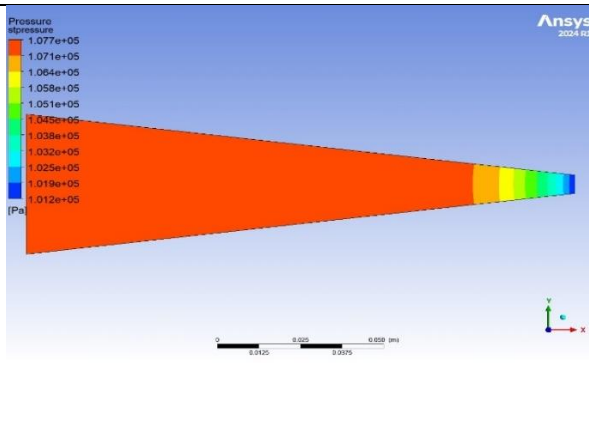
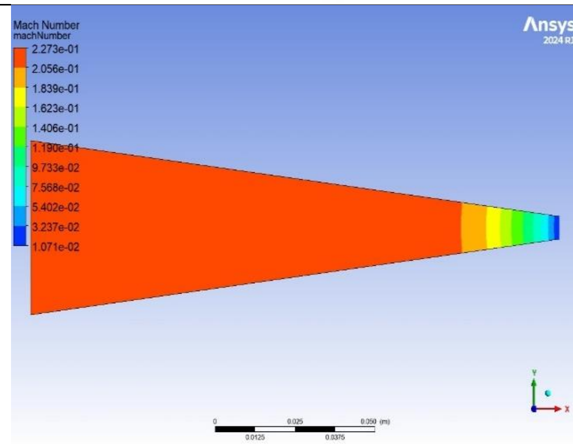
<tr><td>2</td><td>
</td><td>
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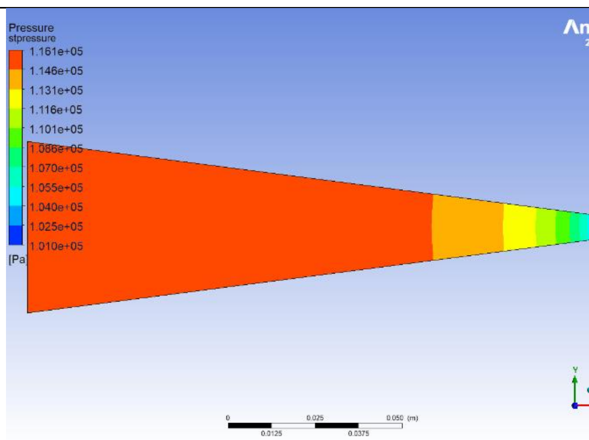
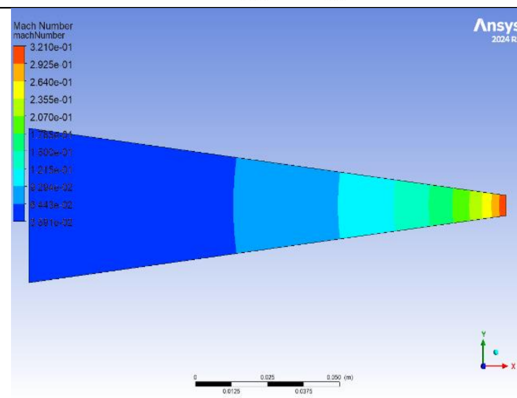
<tr><td>3</td><td>
</td><td>
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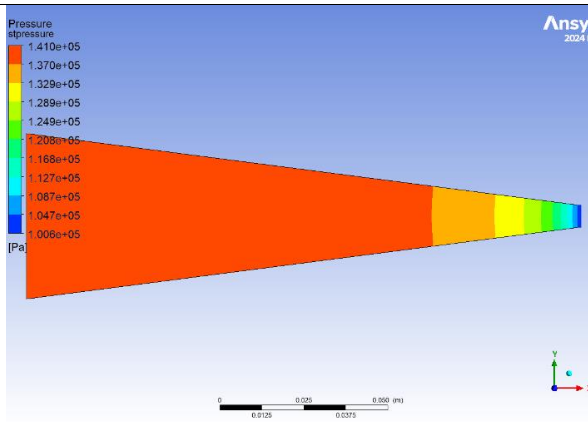
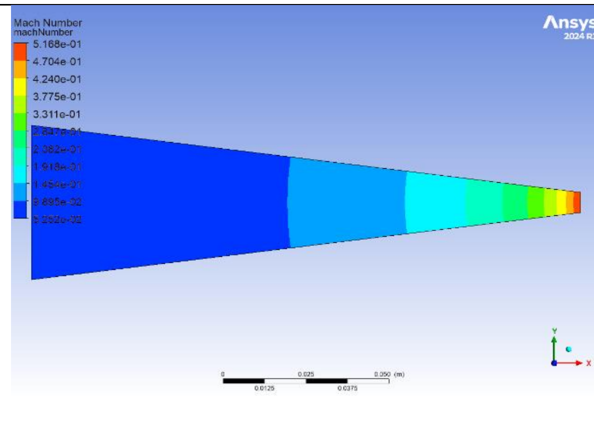
<tr><td>4</td><td>
</td><td>
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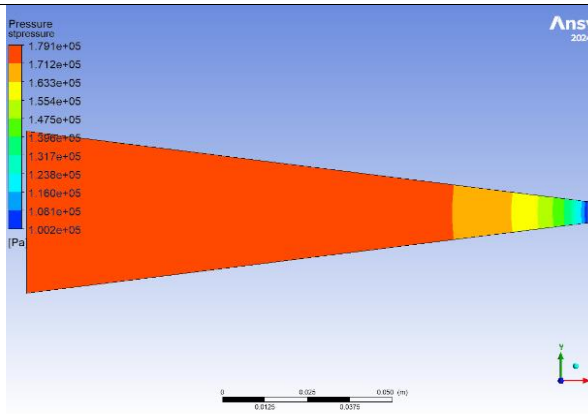
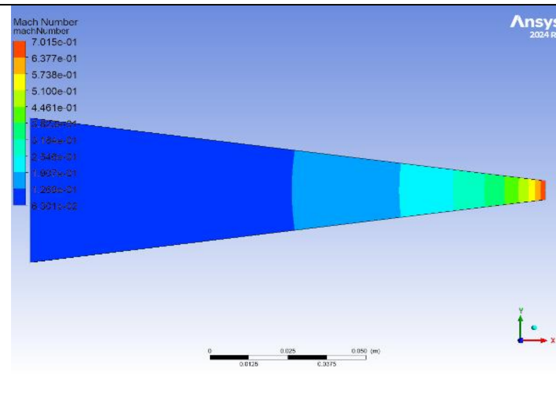
<tr><td>5</td><td>
</td><td>
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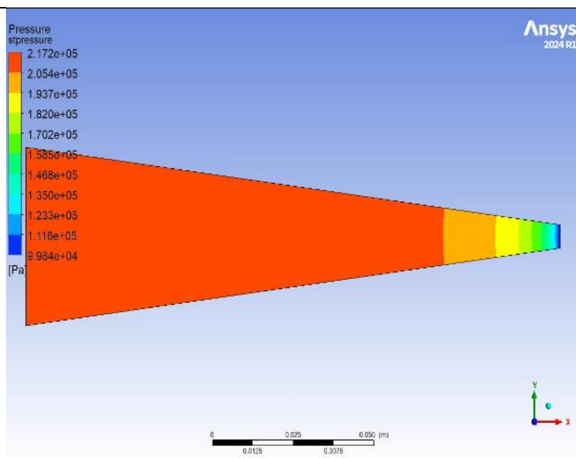
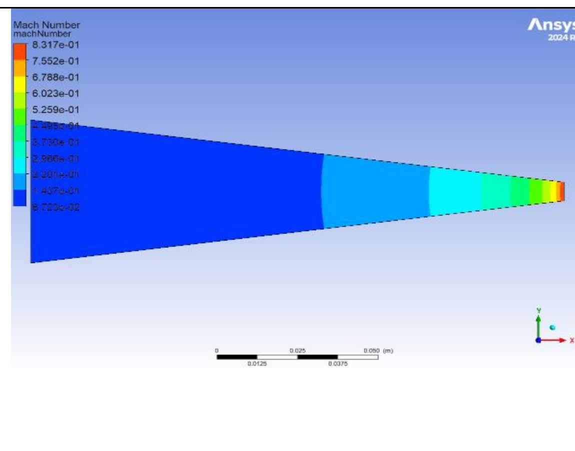
<tr><td>6</td><td>
</td><td>
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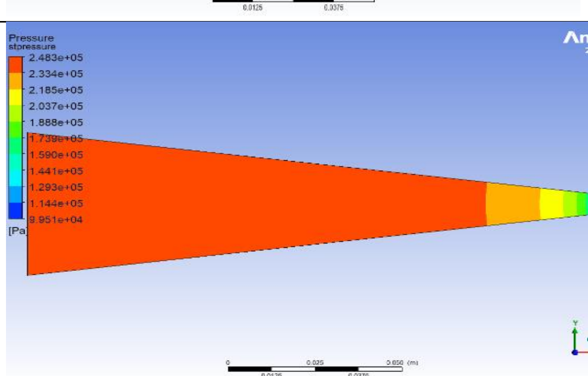
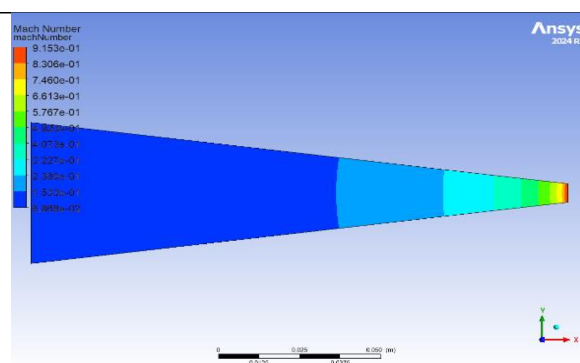
<tr><td>7</td><td>
</td><td>
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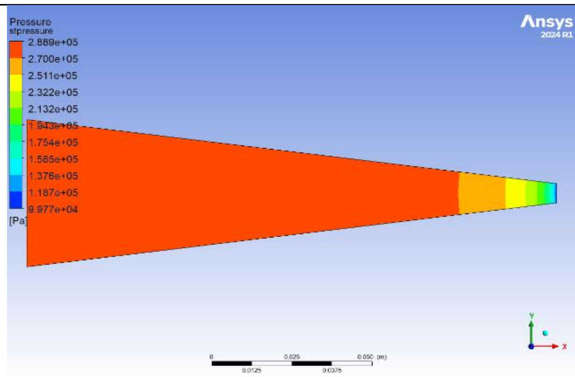
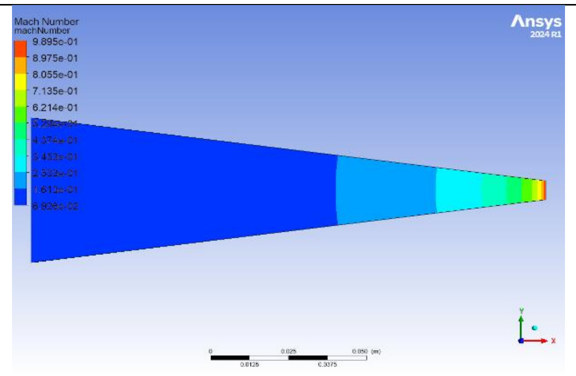
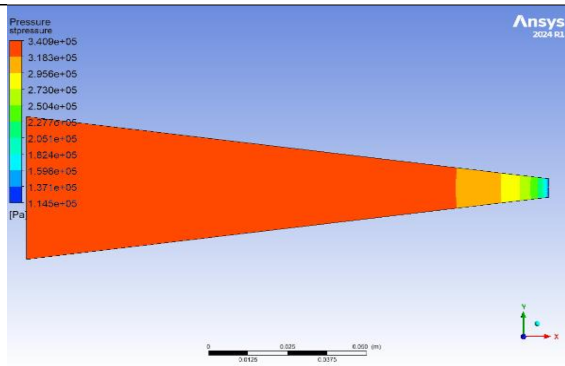
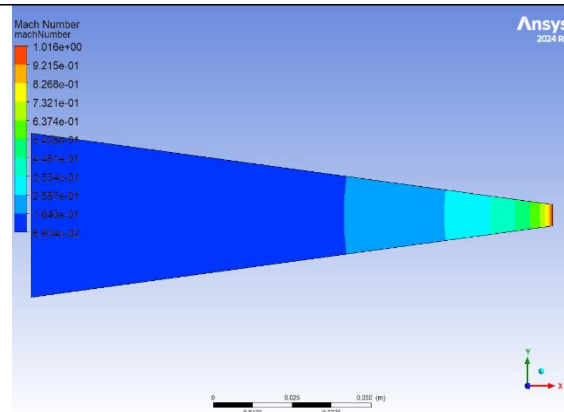
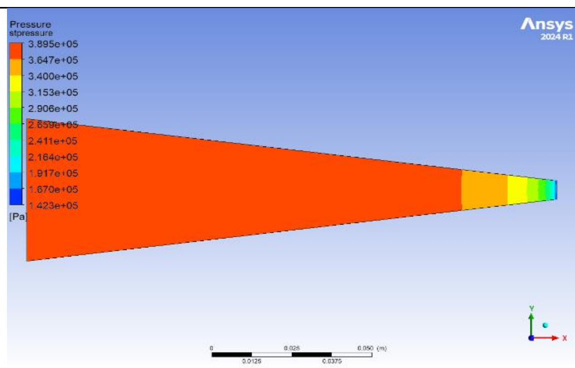
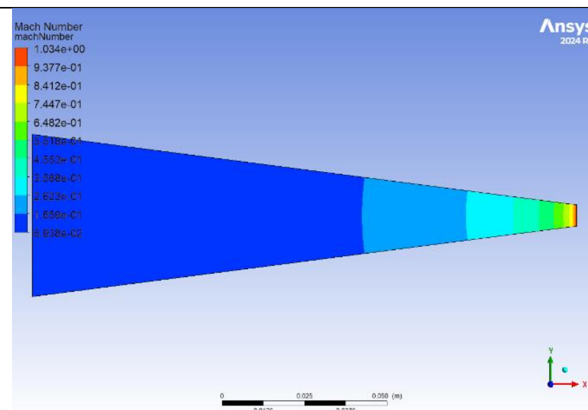
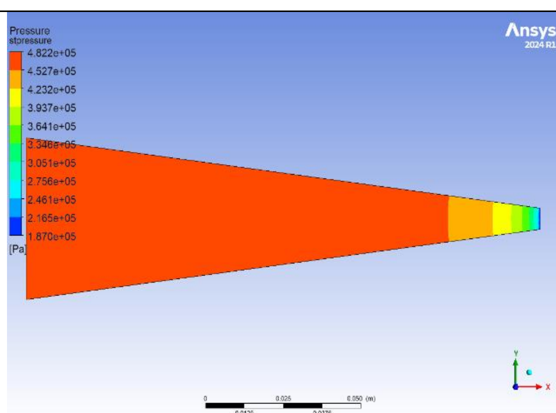
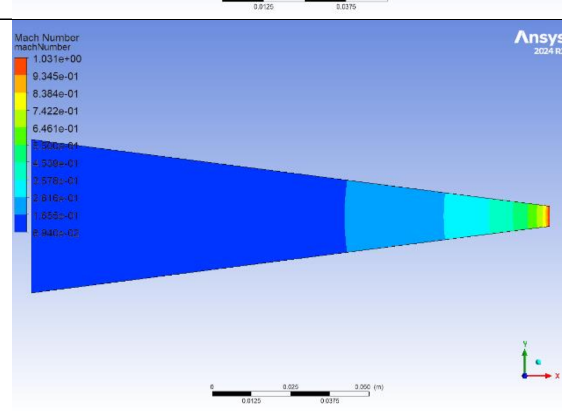
8	Pressure stpressure Ansys 2024 R1 2.889e+05 2.700e+05 2.511e+05 2.322e+05 2.132e+05 1.943e+05 1.754e+05 1.565e+05 1.376e+05 1.187e+05 9.977e+04 [Pa]	Mach Number machNumber Ansys 2024 R1 9.895e-01 8.975e-01 8.055e-01 7.135e-01 6.214e-01
9	Pressure stpressure Ansys 2024 R1 3.409e+05 3.183e+05 2.956e+05 2.730e+05 2.504e+05 2.277e+05 2.051e+05 1.824e+05 1.598e+05 1.371e+05 1.145e+05 [Pa]	Mach Number machNumber Ansys 2024 R1 1.016e+00 9.215e-01 8.268e-01 7.321e-01 6.374e-01
10	Pressure stpressure Ansys 2024 R1 3.895e+05 3.647e+05 3.400e+05 3.153e+05 2.906e+05 2.659e+05 2.411e+05 2.164e+05 1.917e+05 1.670e+05 1.423e+05 [Pa]	Mach Number machNumber Ansys 2024 R1 1.034e+00 9.377e-01 8.412e-01 7.447e-01 6.482e-01
11	Pressure stpressure Ansys 2024 R1 4.822e+05 4.527e+05 4.232e+05 3.937e+05 3.641e+05 3.346e+05 3.051e+05 2.756e+05 2.461e+05 2.165e+05 1.870e+05 [Pa]	Mach Number machNumber Ansys 2024 R1 1.031e+00 9.345e-01 8.384e-01 7.422e-01 6.461e-01

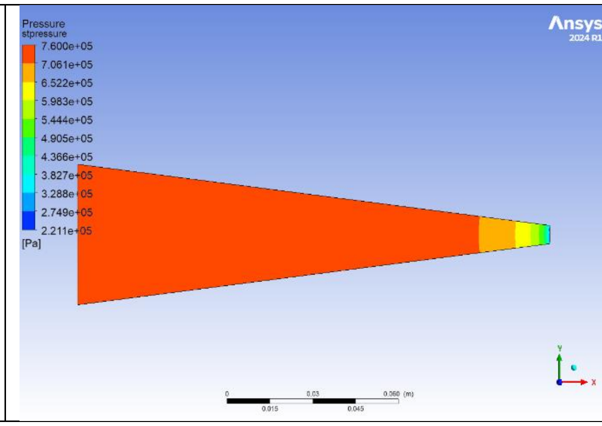
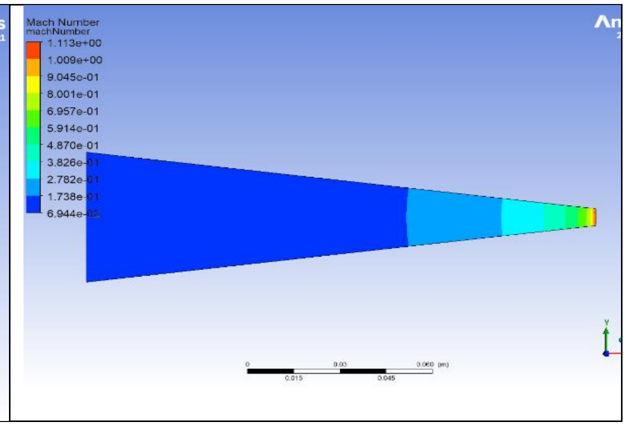
12		

Figure 4: Contours of pressure (left) and Mach number (right) for the C nozzle

III. CD Nozzle

Looking at the experimental data in figure 6, at a normalized distance of about 0.5, the ratio p/p_0 starts to drop. As the flow advances deeper in the nozzle, the pressure ratio gets closer to zero, as the Mach number increases. This is explained by the drop of static pressure as the velocity of the flow increases.

At about run 9 of the computational results, the flow beyond the throat becomes unstable. The pressure ratio jumps up and down until reaching the outlet. Past run 9, the flow behaves roughly the same. In figure 6, the computational flow past run 9 is not visible, but after zooming in, the plots become visible.

Compared to the experimental results, the pressure ratio is in general lower for the computational results. At about run 4, the flow undergoes a supersonic shock in the upper part of the CD nozzle, hence the sudden increase in pressure ratios. The gap between supersonic ratio and subsonic ratio is higher for the computational results because the walls in the simulation are straighter. Therefore, the flow undergoes a sudden normal shock, while for the experimental nozzle, the walls are rounder, which results in a smoother transition to subsonic. In the experimental case, the flow might have had a series of oblique shocks before reaching a subsonic speed. Beyond the choked condition, the pressure does not go back up until the flow reaches the outlet.

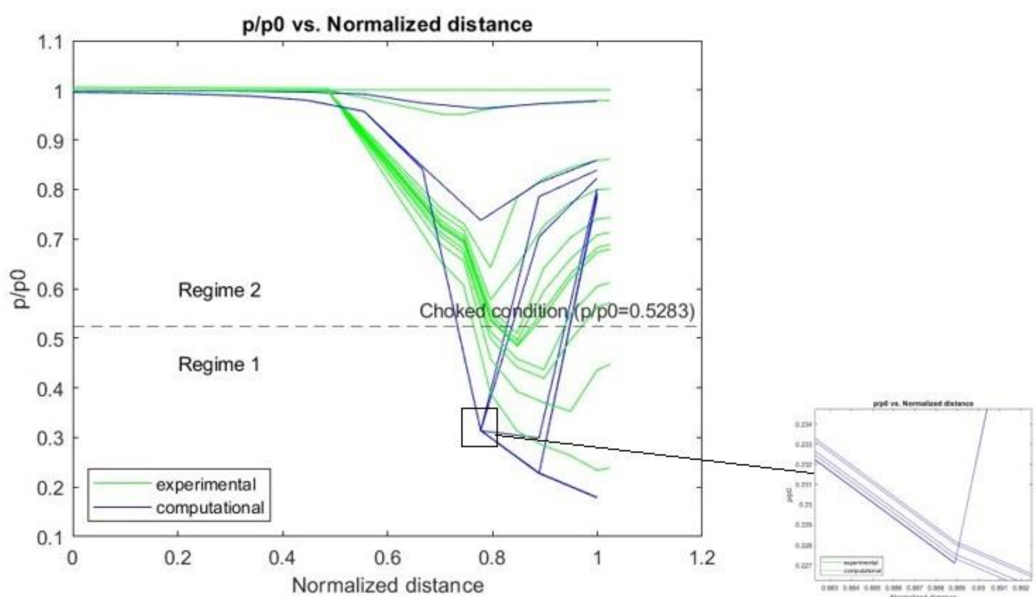


Figure 5: Plot representing p/p_0 vs. normalized distance for a CD nozzle

Figure 7 reflects what is shown in Figure 6. Mach number increases as static pressure decreases. In general, the pressure ratios seem to be lower in the computational simulations than in the experimental ones. They drop faster because of the straight walls of the computational nozzle. The smooth rounded walls in the experimental nozzle allow a smoother transition of the flow. Also, with viscosity neglected for the computations, Mach number is higher, as shown in figure 7. When the Mach number drops back down, the flow has gone through a shockwave.

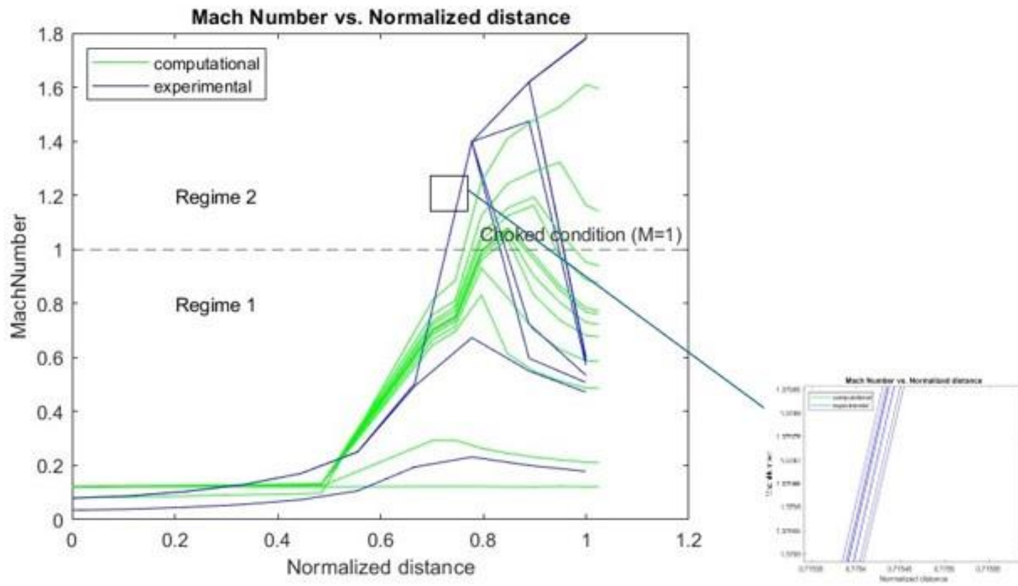


Figure 6: Plot representing Mach Number vs. Normalized distance for a CD nozzle

In figure 8, the MFP vs. p_B/p_0 graph is represented. The MFP is at its maximal value when the chocked condition is reached. As the back pressure gets closer to the total pressure, the MFP drops because as the velocity drops, the static pressure becomes higher and gets closer to p_0 (p_B/p_0 gets closer to 1).

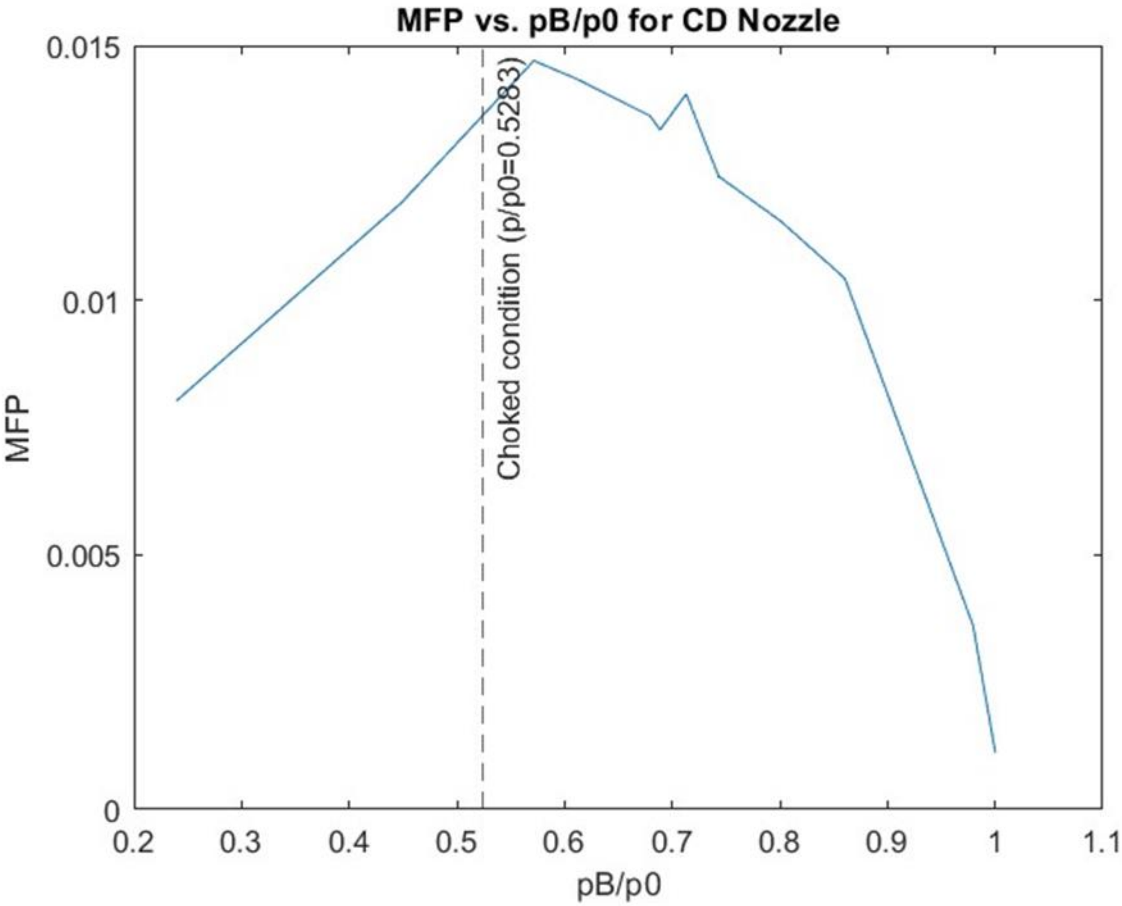


Figure 7: Plot representing MFP vs. p_B/p_0 for CD nozzle

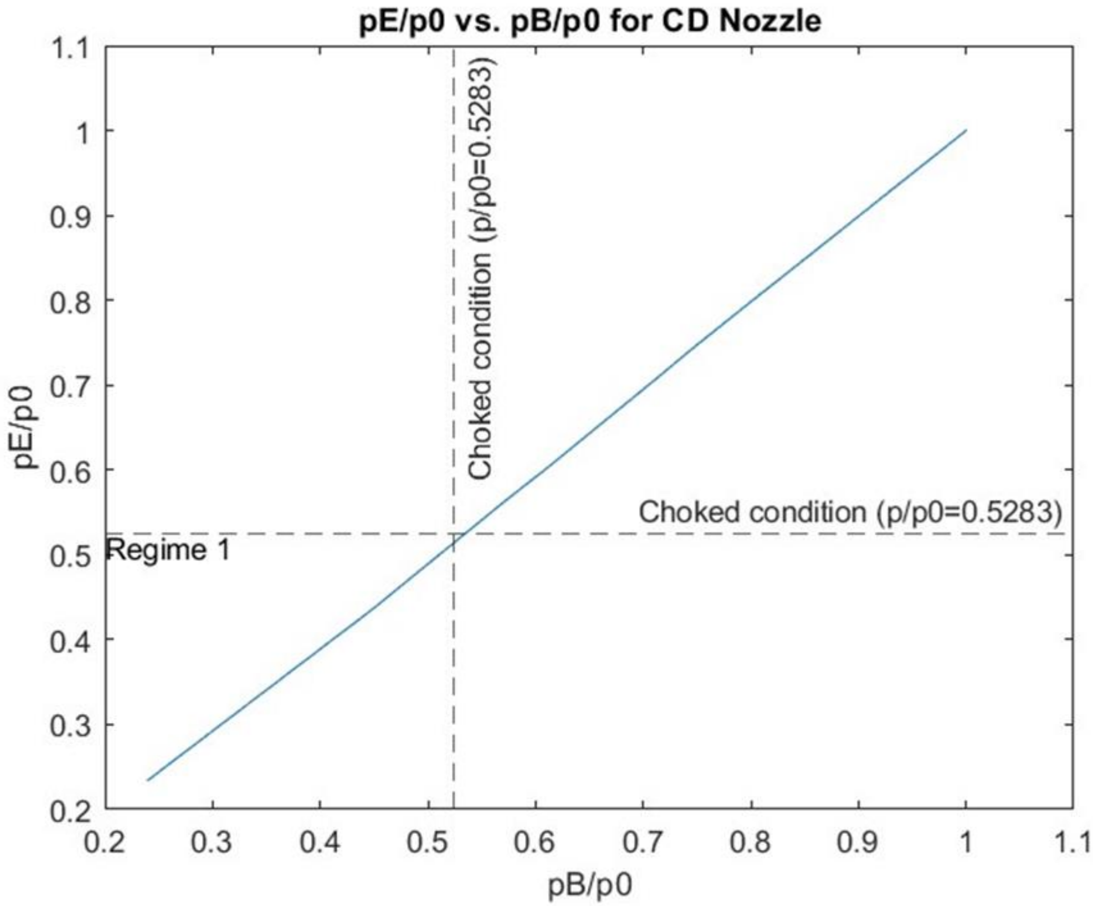


Figure 8: Plot representing p_E/p_0 vs p_B/p_0 for CD nozzle

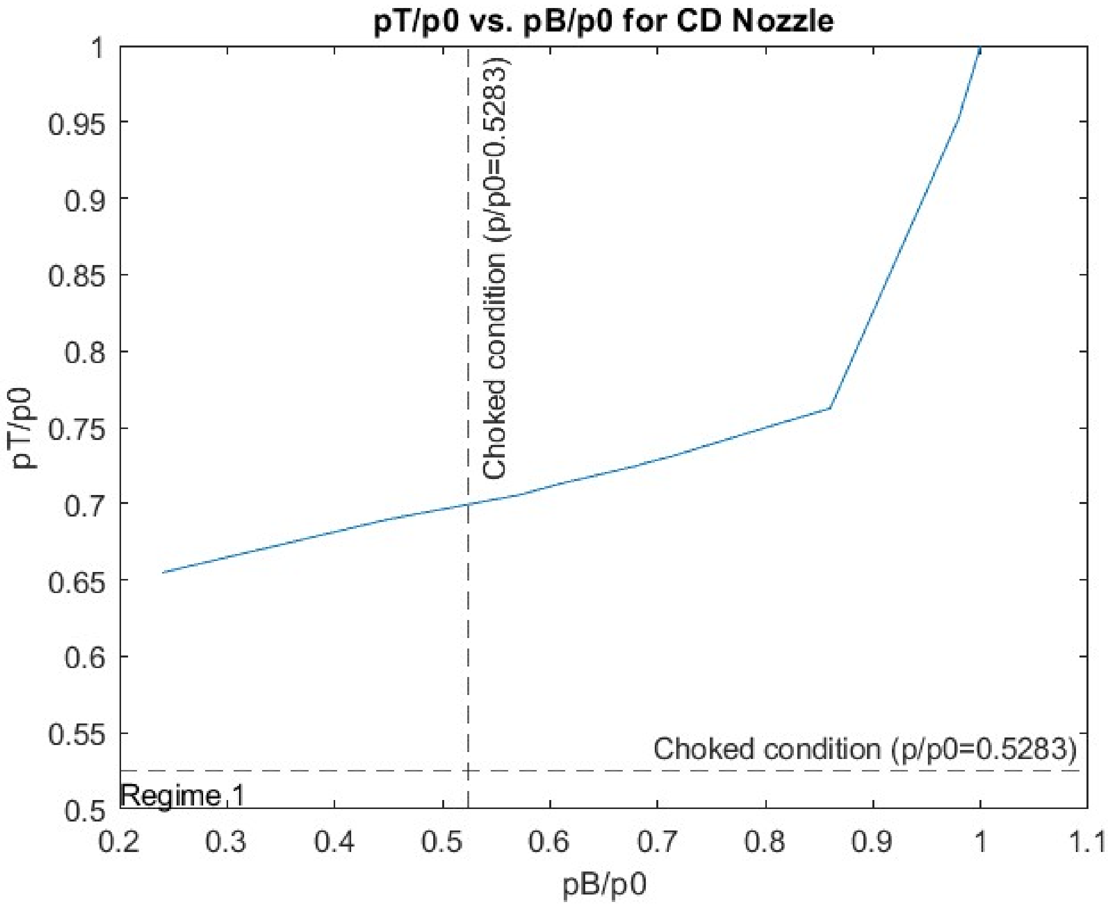


Figure 9: Plot representing p_T/p_0 vs. p_B/p_0 for CD Nozzle

In figure 10, it can be observed that the transition line between a high pressure to a low pressure (between red and orange) is getting closer to the throat as the inlet pressure increases. The mass flow being really high at the beginning and maintained, it is not until a lower area is reached that the velocity starts increasing (increase in velocity means decrease in static pressure). A correspondence can be made with the Mach number contours: an increase in static pressure implies a decrease in Mach number. On the diverging side of the nozzle, from runs 4 to 8, a normal shockwave can be seen. It is represented by a sudden drop of the Mach number. Beyond inlet pressure of run 8, the shockwave occurs outside of the nozzle. It can be concluded that the most convinent ratio p_B/p_0 is 0.679477 if we want the normal shock to happen near the outlet.

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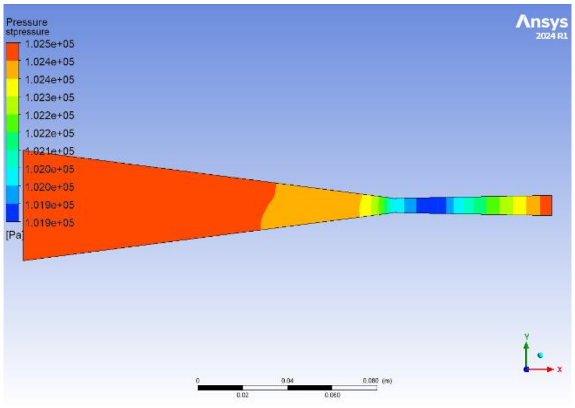
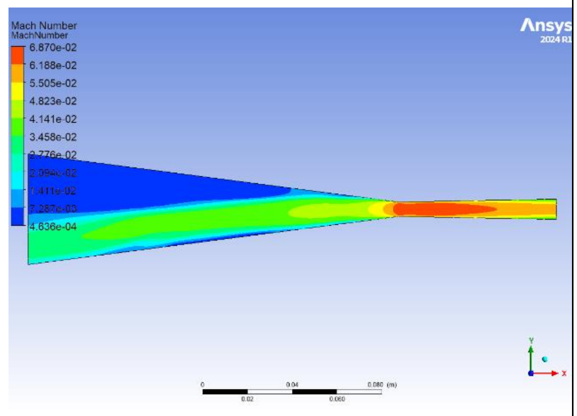
<tr><td>1</td><td>
</td><td>
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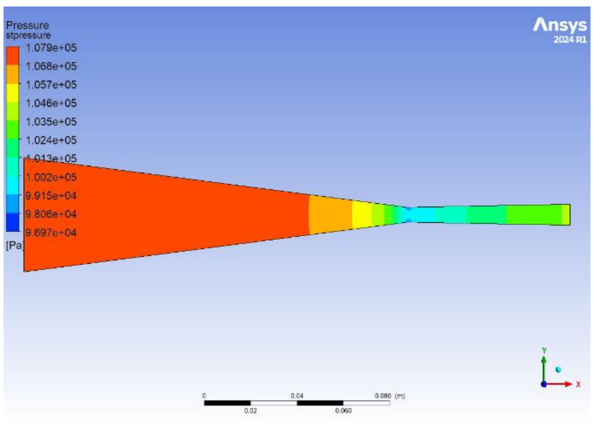
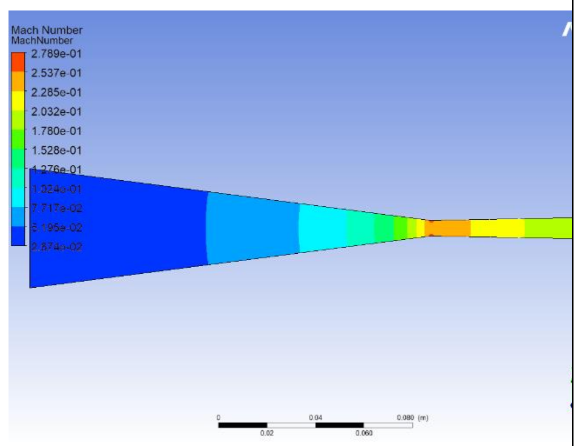
<tr><td>2</td><td>
</td><td>
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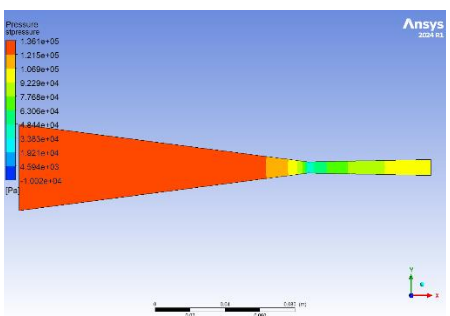
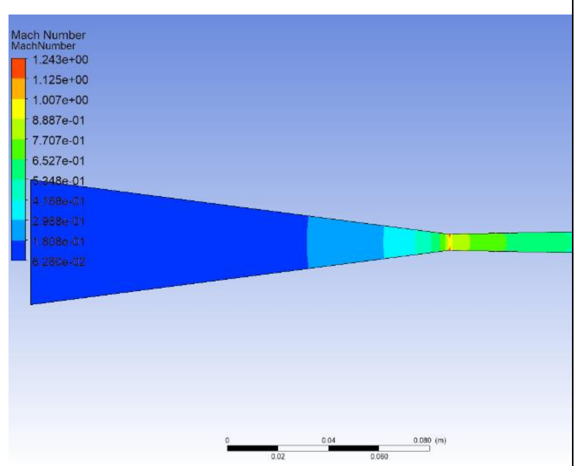
<tr><td>3</td><td>
</td><td>
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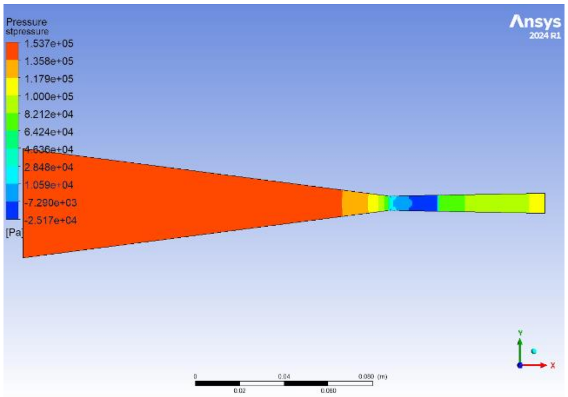

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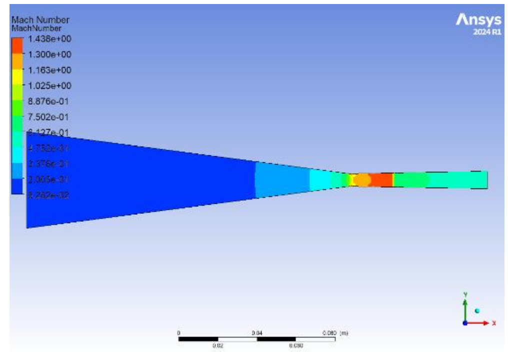
Ansys
2024 R1



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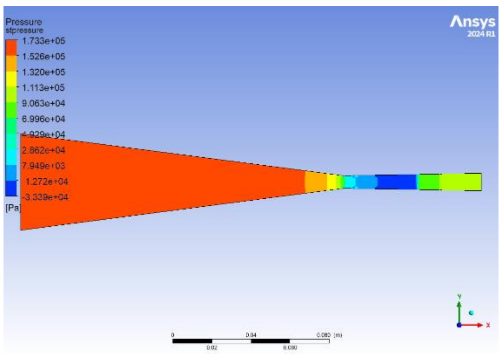

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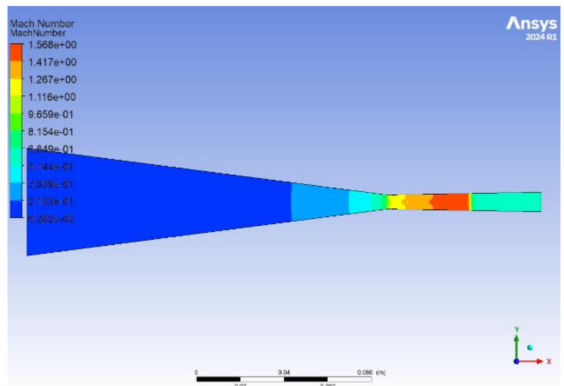

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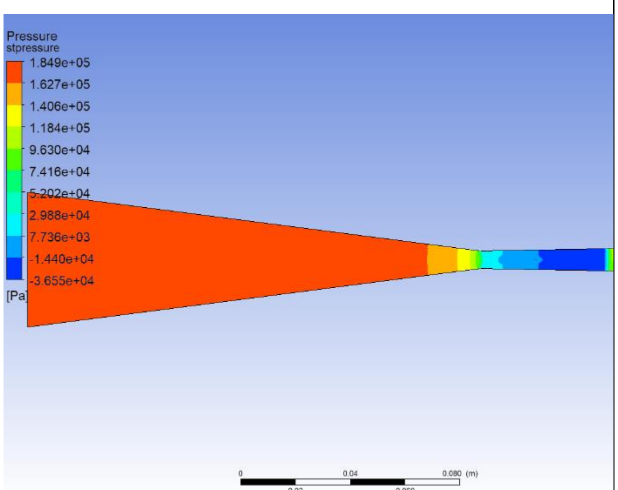

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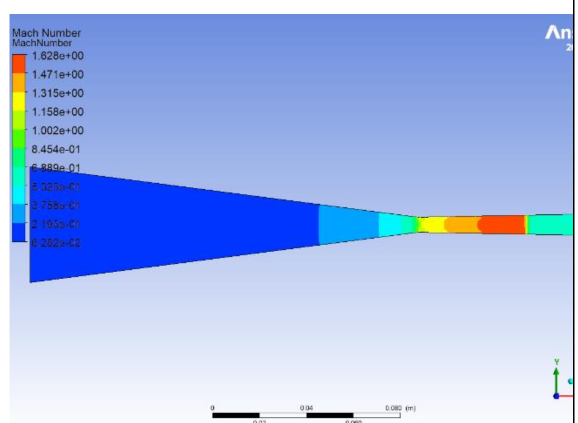

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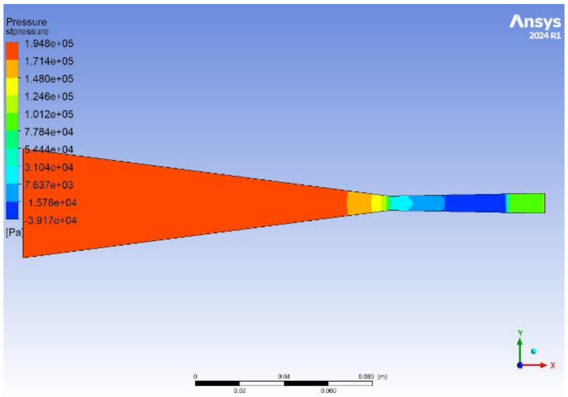
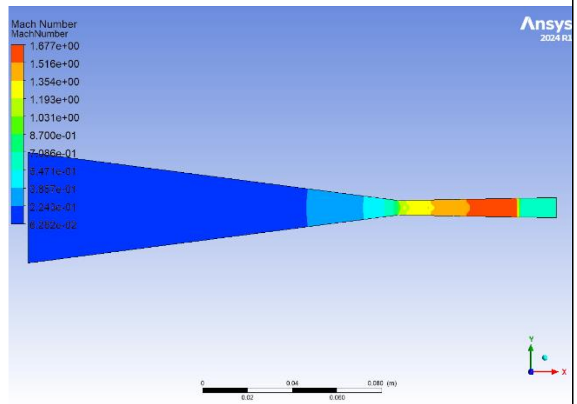
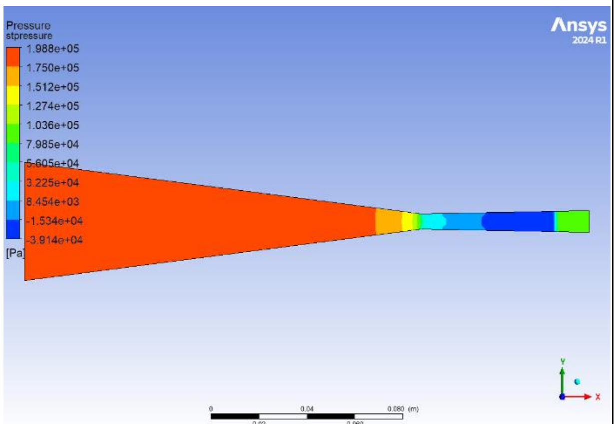
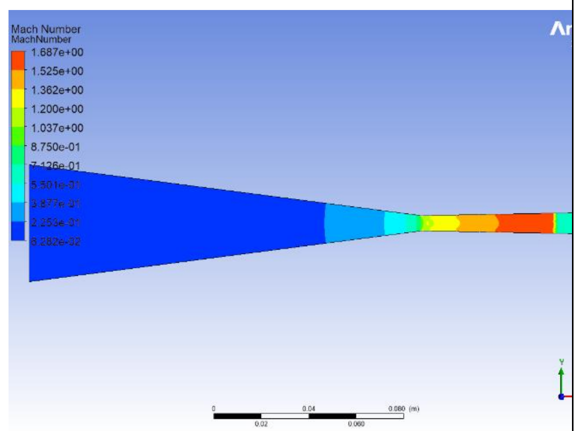
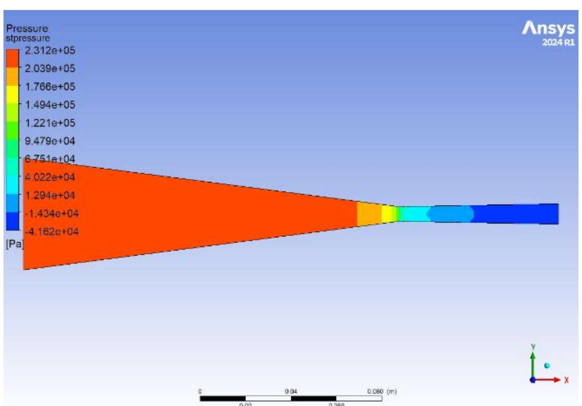
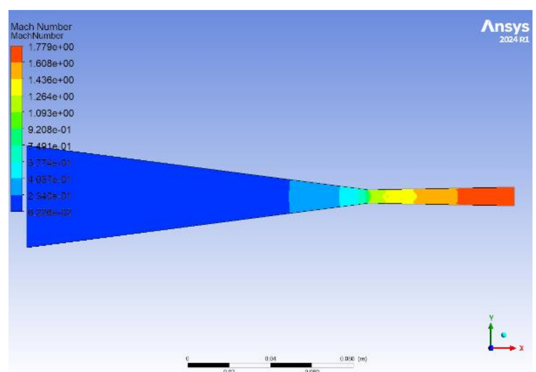
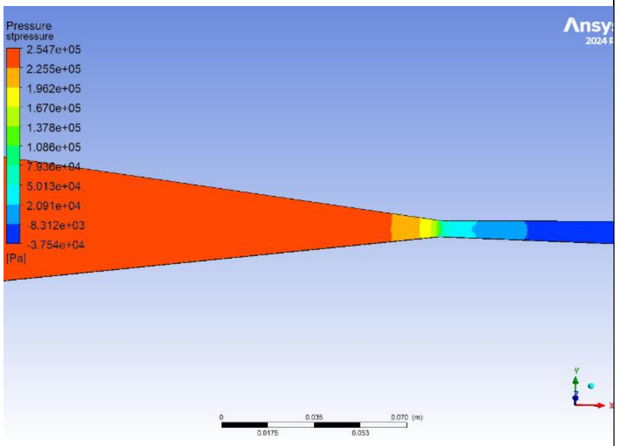
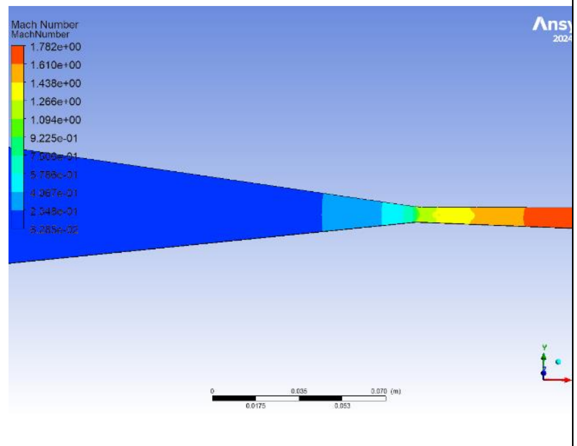
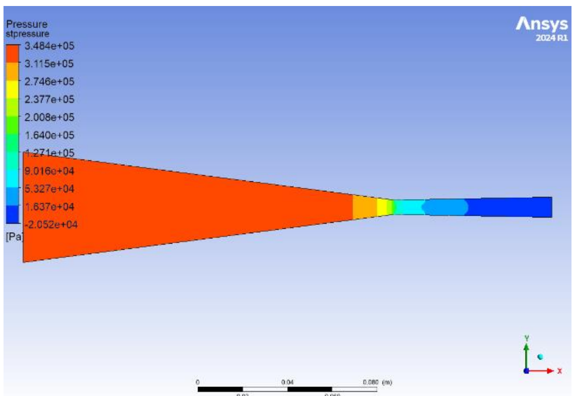
7	Pressure stpressure 1.948e+05 1.714e+05 1.480e+05 1.246e+05 1.012e+05 7.784e+04 5.444e+04 3.104e+04 7.637e+03 1.578e+04 -3.917e+04 [Pa] Ansys 2024 R1	Mach Number MachNumber 1.677e+00 1.516e+00 1.354e+00 1.193e+00 1.031e+00 8.700e-01 Ansys 2024 R1
8	Pressure stpressure 1.988e+05 1.750e+05 1.512e+05 1.274e+05 1.036e+05 7.985e+04 5.605e+04 3.225e+04 8.454e+03 -1.534e+04 -3.914e+04 [Pa] Ansys 2024 R1	Mach Number MachNumber 1.687e+00 1.525e+00 1.362e+00 1.200e+00 1.037e+00 8.750e-01
9	Pressure stpressure 2.312e+05 2.039e+05 1.766e+05 1.494e+05 1.221e+05 9.479e+04 6.751e+04 4.022e+04 1.294e+04 -1.434e+04 -4.162e+04 [Pa] Ansys 2024 R1	Mach Number MachNumber 1.779e+00 1.608e+00 1.436e+00 1.264e+00 1.093e+00 9.208e-01 Ansys 2024 R1

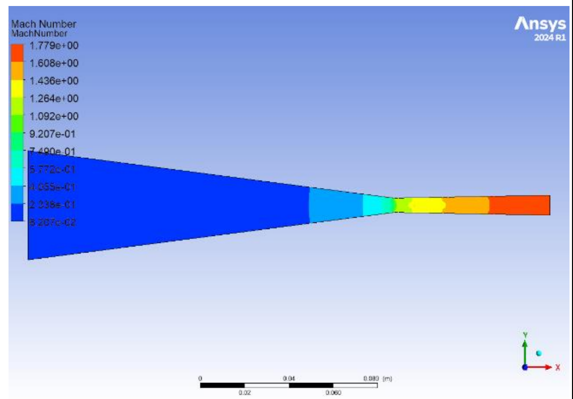
10



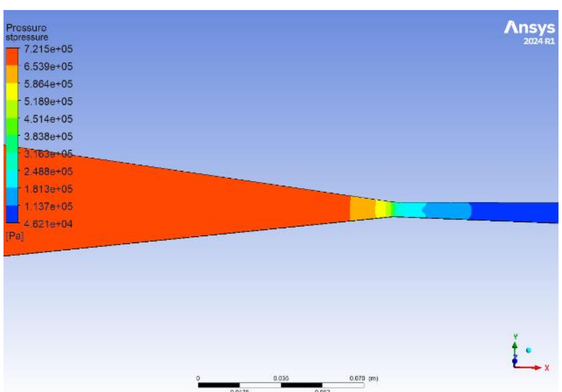


11





12



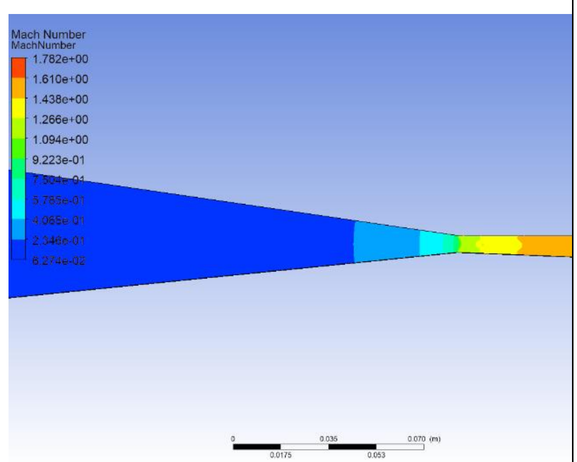


Figure 10: Contours of pressure (left) and Mach number (right) for CD nozzle

IV. Conclusion

Experimental results always need to be validated using computationa results. Computational results are not often perfect but a general behavior can be observed from both computational and experimental experiments. The differences observed here are mainly due to the shape of the nozzle (straight walls in the computer case vs rounded walls in the experimental case). The parameters chosen in ANSYS can also affect the results: inviscid flow was chosen to simulate the flow.

Appendix

Appendix A: code for C nozzle

```
gamma = 1.4;
T0 = 295;
R = 287;
Ai = 3.17e-5;
figure(1)
myarray = zeros(1,12);
myMFP = zeros(1,12);
atmpressure = 100725;


for i = 1:12
    letter = int2str(i)+".txt";
    ext2 = int2str(i)+".csv";
    ending = letter;
    t = readtable("experimental-data/CNozzle/run_"+ending);

    %{
    u = readtable("computational-data/Cnozzle/run_"+ext2);
    x2 = u{:,4};
    x2 = x2./0.1651;
    %}


    x1 = t{:,3};
    x1 = x1./6.5;
    ps = t{:,5};
    patm = t{:,8};
    newpstat = patm + ps;
    p0 = t{:,6};
    newp0 = p0 + patm;
    pRatio = newpstat ./ newp0;


    %{
    pRatio2 = (u{:,2}+atmpressure)./(u{:,3}+atmpressure);
    plot(x2,pRatio2, "blue");
    hold on
    %}

    plot(x1, pRatio, 'green');
    hold on



end

title("p/p0 vs. Normalized distance for C Nozzle");
yline(0.5248, "--", "Choked condition (p/p0=0.5283)");
xlabel('Normalized distance');
ylabel('p/p0');

%{
```

```
legend({"experimental", "computational"}, "Location", "southwest")
%}

text(0.2, 0.45, "Regime 1")
text(0.2, 0.6, "Regime 2")
figure(2)
for i = 1:12
    letter = int2str(i)+".txt";
    ext2 = int2str(i)+".csv";
    t = readtable("experimental-data/CNozzle/run_"+letter);

    %{
    u = readtable("computational-data/Cnozzle/run_"+ext2);
    %}

    sum = nthroot((t{:,8}+t{:,6})./(t{:,5}+t{:,8}), gamma/(gamma-1));
    M = sqrt((sum-0.997).*2./(gamma-1));
    x1 = t{:,3};
    x1 = x1./6.5;
    plot(x1, M, "green");

    %{
    x2 = u{:,4};
    x2 = x2./0.1651;
    MachComp = u{:,1};
    plot(x2, MachComp, "blue");
    %}

    hold on;
end
title("Mach Number vs. Normalized distance for C Nozzle")
yline(1, "--", "Choked condition (M=1)");
xlabel('Normalized distance')
ylabel('MachNumber')

%{
legend({"computational", "experimental"}, "Location", "northwest");
%}

text(0.2, 0.8, "Regime 1")
text(0.2, 1.2, "Regime 2")

figure(3)
for i = 1:12
    letter = int2str(i)+".txt";
    t = readtable("experimental-data/CNozzle/run_"+letter);
    pB = t{10,5}+t{10,8};
    p0 = t{10,6}+t{10,8};
    myarray(1,i) = pB/p0;
    MFP = t{9,7}*sqrt(T0)/Ai/((t{9,6}+t{9,8})*6894.75729);
    myMFP(1,i) = MFP;
end
plot(myarray, myMFP);
title("pB/p0 vs. MFP for C Nozzle")
xlabel('pB/p0');
```

```
ylabel("MFP");
xline(0.5283, "--", "Choked condition (p/p0=0.5283)");
text(0.4, 0.005, "Regime 1")
text(0.8, 0.005, "Regime 2")
```

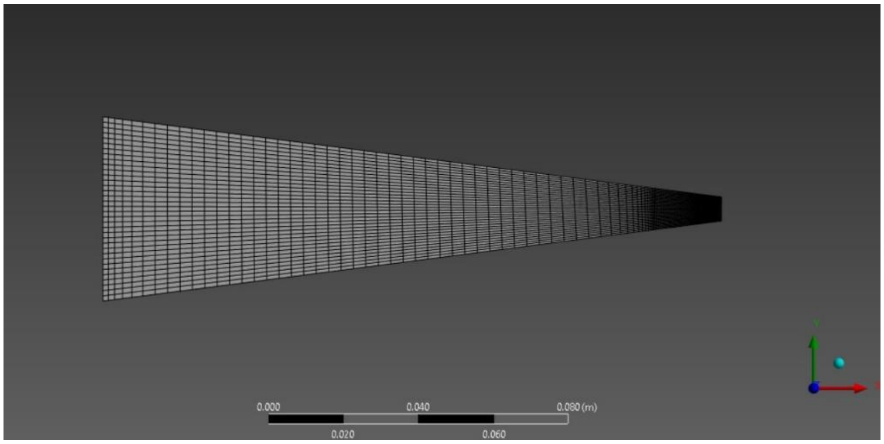
Appendix B: Code for CD Nozzle

```
gamma = 1.4;
T0 = 295;
R = 287;
Ai = 3.17e-5;

myarray = zeros(1,12);
myMFP = zeros(1,12);
myarray2 = zeros(1,12);
myarray3 = zeros(1,12);
myarray4 = zeros(1,12);
myarray5 = zeros(1,12);
disp(myarray);
disp(myMFP);
atmpressure = 100725;
figure(1)
for i = 1:12
    letter = int2str(i)+".txt";
    ext2 = int2str(i)+".csv";
    ending = letter;
    t = readtable("experimental-data/CDNozzle/run_"+ending);
    x1 = t{:,3};
    x1 = x1./9.26771654;



    u = readtable("computational-data/CDnozzle/run_"+ext2);
    x2 = u{:,4};
    x2 = x2./0.2354;
    pRatio2 = (u{:,2}+atmpressure)./(u{:,3}+atmpressure);



    ps = t{:,5};
    patm = t{:,8};
    newpstat = patm + ps;
    p0 = t{:,6};
    newp0 = p0 + patm;
    pRatio = newpstat ./ newp0;

    plot(x1, pRatio, 'green');
    hold on
```

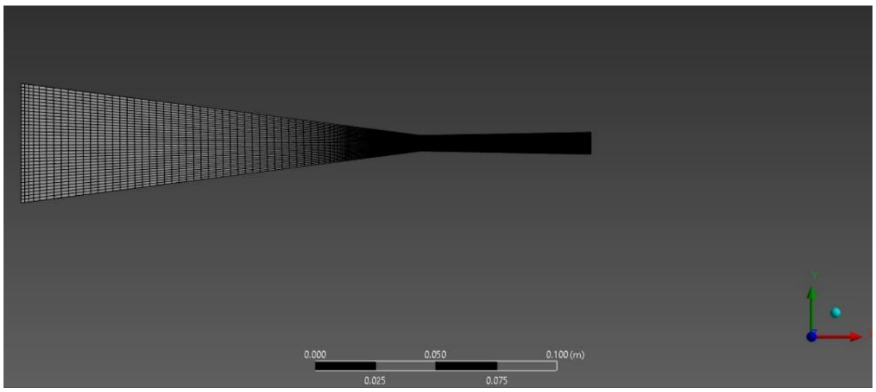
```
    %{
    plot(x2,pRatio2, "blue");
    %}


end
yline(0.5248, "--", "Choked condition (p/p0=0.5283)");
title("p/p0 vs. Normalized distance");
xlabel('Normalized distance');
ylabel('p/p0');
legend({"experimental", "computational"}, "Location", "southwest")
text(0.2, 0.45, "Regime 1")
text(0.2, 0.6, "Regime 2")
hold off
figure(2)

for i = 1:12
    letter = int2str(i)+".txt";
    ext2 = int2str(i)+".csv";
    t = readtable("experimental-data/CDNozzle/run_"+letter);

    %{
    u = readtable("computational-data/CDnozzle/run_"+ext2);
    %}


    sum = nthroot((t{:,8}+t{:,6})./(t{:,5}+t{:,8}), gamma/(gamma-1));
    M = sqrt((sum-0.997).*2./(gamma-1));
    x1 = t{:,3};
    x1 = x1./9.26771654;
    plot(x1, M, "green");
    hold on

   %{
    x2 = u{:,4};
    x2 = x2./0.2354;
    MachComp = u{:,1};
    plot(x2, MachComp, "blue");
    hold on;
    %}


end
title("Mach Number vs. Normalized distance")
yline(1, "--", "Choked condition (M=1)");
xlabel('Normalized distance')
ylabel('MachNumber')

%{legend({"computational", "experimental"}, "Location", "northwest");%}

text(0.2, 0.8, "Regime 1")
text(0.2, 1.2, "Regime 2")

figure(3)
for i = 1:12
```

```
    letter = int2str(i)+".txt";
    t = readtable("experimental-data/CDNozzle/run_"+letter);
    pB = t{10,5}+t{10,8};
    p0 = t{10,6}+t{10,8};
    myarray(1,i) = pB/p0;
    MFP = t{9,7}*sqrt(T0)/Ai/((t{9,6}+t{9,8})*6894.75729);
    myMFP(1,i) = MFP;
end
plot(myarray, myMFP);
title("MFP vs. pB/p0 for CD Nozzle")
xlabel('pB/p0');
ylabel("MFP");
xline(0.5248, "--", "Choked condition (p/p0=0.5283)");



figure(4)
for i = 1:12
    letter = int2str(i)+".txt";
    t = readtable("experimental-data/CDNozzle/run_"+letter);
    pB = t{10,5}+t{10,8};
    p0 = t{10,6}+t{10,8};
    pE = t{9,5} + t{9,8};
    pT = t{3,5} + t{3,8};
    myarray2(1,i) = pE/p0;
    myarray3(1,i) = pT/p0;
end
plot(myarray, myarray2);
title("pE/p0 vs. pB/p0 for CD Nozzle")
xlabel("pB/p0")
ylabel("pE/p0")
yline(0.5248, "--", "Choked condition (p/p0=0.5283)");
xline(0.5248, "--", "Choked condition (p/p0=0.5283)");
text(0.2, 0.51, "Regime 1")
figure(5);
plot(myarray, myarray3)
title("pT/p0 vs. pB/p0 for CD Nozzle")
xlabel("pB/p0");
ylabel("pT/p0");
yline(0.5248, "--", "Choked condition (p/p0=0.5283)");
xline(0.5248, "--", "Choked condition (p/p0=0.5283)");
text(0.2, 0.51, "Regime 1")
```

Appendix C: Grids



Grid for C nozzle



Grid for CD Nozzle

References

[1] Ansys Inc. Workbench with Speos 2024 R1. Canonsburg, Pennsylvania
[2] Mathworks. MATLAB Version R2024B. Natick, Massachusetts