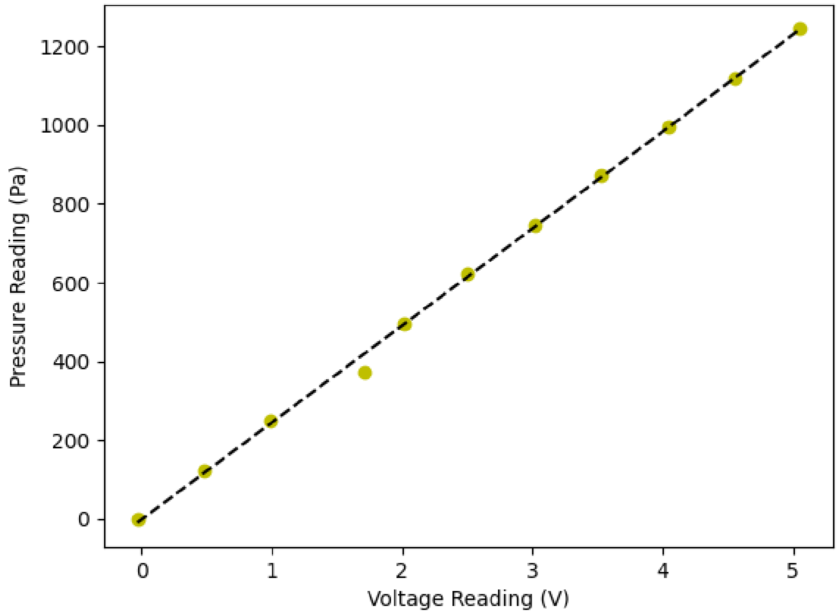
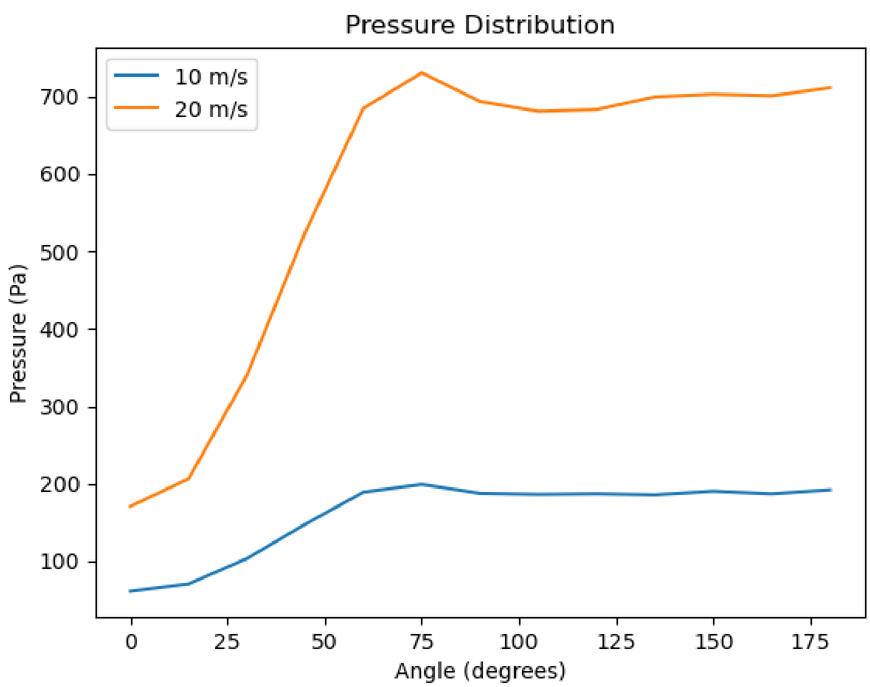
# Fluids Lab 3 - Individual Calculations (12” Wind Tunnel)

Kieran Cosgrove

Linear Fit of Voltage to Pressure




Pressure Distribution Graphs




Static pressure voltage measurements along the surface of the cylinder at different angles are converted to pascals using above linear fit, and then plotted against angle.

Pressure Coefficient Sample Calculation

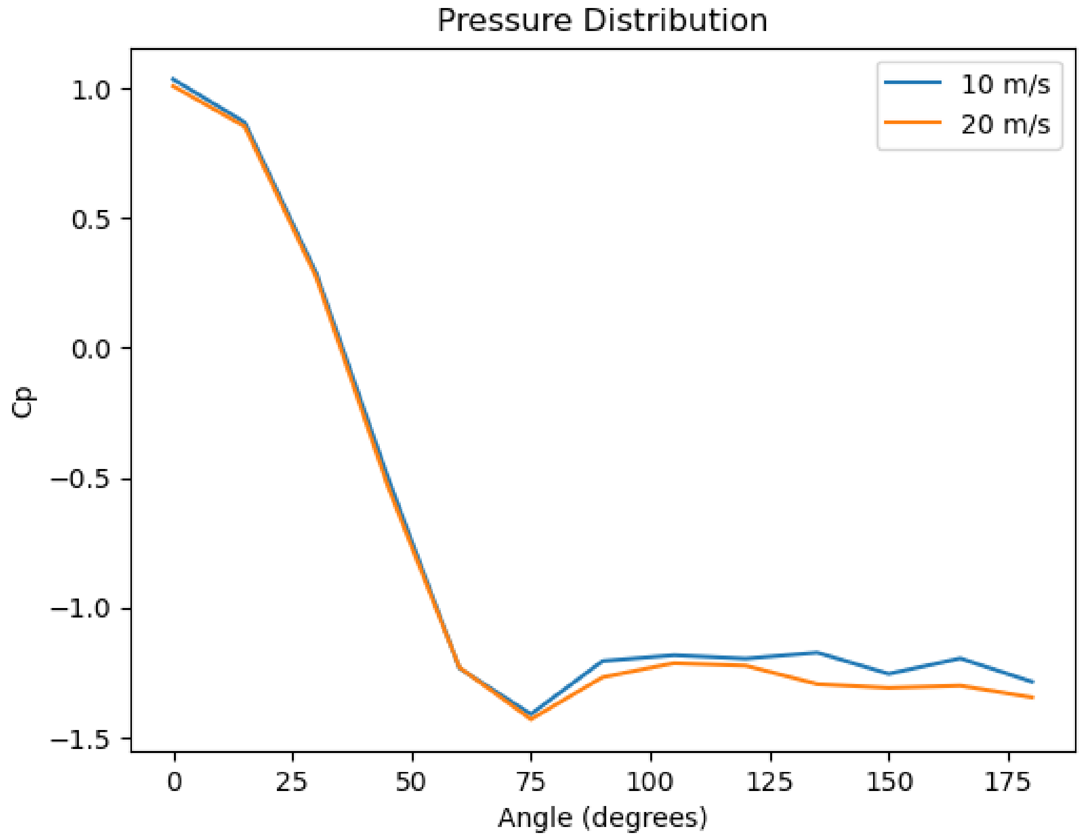
$C_p$ = (surface pressure - upstream static pressure) / (upstream dynamic pressure)

$C_p$ @ $0^o$ - 20 m/s = (-174.188 Pa + 408.098 Pa) / 233.91 Pa

$C_p = 1$

$C_p$ @ $90^o$ - 20 m/s = (-701.7288 Pa + 408.098 Pa) / 233.91 Pa

$C_p = -1.255$




Pressure coefficient determined using the same formula in sample calculation along the surface of the cylinder at different angles and plotted against angle.

Pressure Distribution Sample Integration

Using the integral pictured below with trapezoidal numerical integration as in the spreadsheets below and attached, the drag force was found to be 0.415 N and 1.763 N for 10 m/s and 20 m/s flow speeds, respectively. ‘L’ and ‘D’ were converted to metric, the average of P*cos(theta) between two positions was used to determine the average height for the numerical integration, times the step size which is the change in theta in degrees. The pressure used was the absolute pressure, which was the absolute pressure of 100.5 kPa minus the gauge pressure.

$$F_D = \int dF_x \qquad = \frac{2\pi D}{360} L \int_0^{180} P\cos\theta \, d\theta$$

| Theta (degrees) | 10 m/s pressure gauge (Pa) | absolute (Pa) | 10 m/s step force |
|---|---|---|---|
| 0 | 61.11763373 | 100438.88237 | 150.968866167417 |
| 15 | 70.47666902 | 100429.52333 | 140.651091221238 |
| 30 | 103.2332925 | 100396.76671 | 120.733467796946 |
| 45 | 147.5655649 | 100352.43444 | 92.6024495814621 |
| 60 | 189.0408687 | 100310.95913 | 58.1974005962013 |
| 75 | 199.040259 | 100300.95974 | 19.850201461799 |
| 90 | 187.5056585 | 100312.49434 | -19.8514686925248 |
| 105 | 186.2331581 | 100313.76684 | -58.2017160978013 |
| 120 | 186.9720293 | 100313.02797 | -92.5858251357138 |
| 135 | 185.6584805 | 100314.34152 | -120.658211639407 |
| 150 | 190.2723207 | 100309.72768 | -140.508572229661 |
| 165 | 186.9309809 | 100313.06902 | -150.782987714277 |
| 180 | 191.9799341 | 100308.02007 | |
| | | Force (N): | 0.414695315679921 |

| Theta (degrees) | 20 m/s pressure gauge (Pa) | absolute (Pa) | 20 m/s step force |
|---|---|---|---|
| 0 | 170.6676047 | 100329.3323953 | 150.78441303944 |
| 15 | 206.3468743 | 100293.6531257 | 140.39024160448 |
| 30 | 339.8128161 | 100160.1871839 | 120.36449439126 |
| 45 | 524.4954334 | 99975.5045666 | 92.199708906907 |
| 60 | 684.8234484 | 99815.1765516 | 57.899359480796 |
| 75 | 730.6334633 | 99769.3665367 | 19.747533840024 |
| 90 | 693.50929 | 99806.49071 | -19.752445983746 |
| 105 | 680.9895279 | 99819.0104721 | -57.914218429157 |
| 120 | 683.2471899 | 99816.7528101 | -92.119673858761 |
| 135 | 699.5023564 | 99800.4976436 | -120.04089587649 |
| 150 | 702.8683253 | 99797.1316747 | -139.78957780295 |
| 165 | 700.9390504 | 99799.0609496 | -150.006376739 |
| 180 | 711.2750377 | 99788.7249623 | |
| | | Force (N): | 1.7625625727921 |

Pressure Coefficient Sample Calculation

$C_D$ = (drag force) / ((dynamic pressure) * (area))

area = length * diameter of cylinder

$C_D$ @ 20 m/s = 1.763 N / (229.827 Pa * 0.3048 m * 0.019 m)

$C_D$ = **1.325**

$C_D$ @ 10 m/s = 0.415 N / (56.438 Pa * 0.3048 m * 0.019 m)

$C_D$ = **1.270**

Control Volume Graphs

Measured dynamic pressure voltages upstream and downstream of the cylinder are taken, averaged, and converted to pressures using the earlier linear fit. These pressures are then converted into velocities using the dynamic pressure equation given by:

$$\frac{1}{2}\rho U^2$$

These velocities were then graphed against their position vertically upstream and downstream of the cylinder.

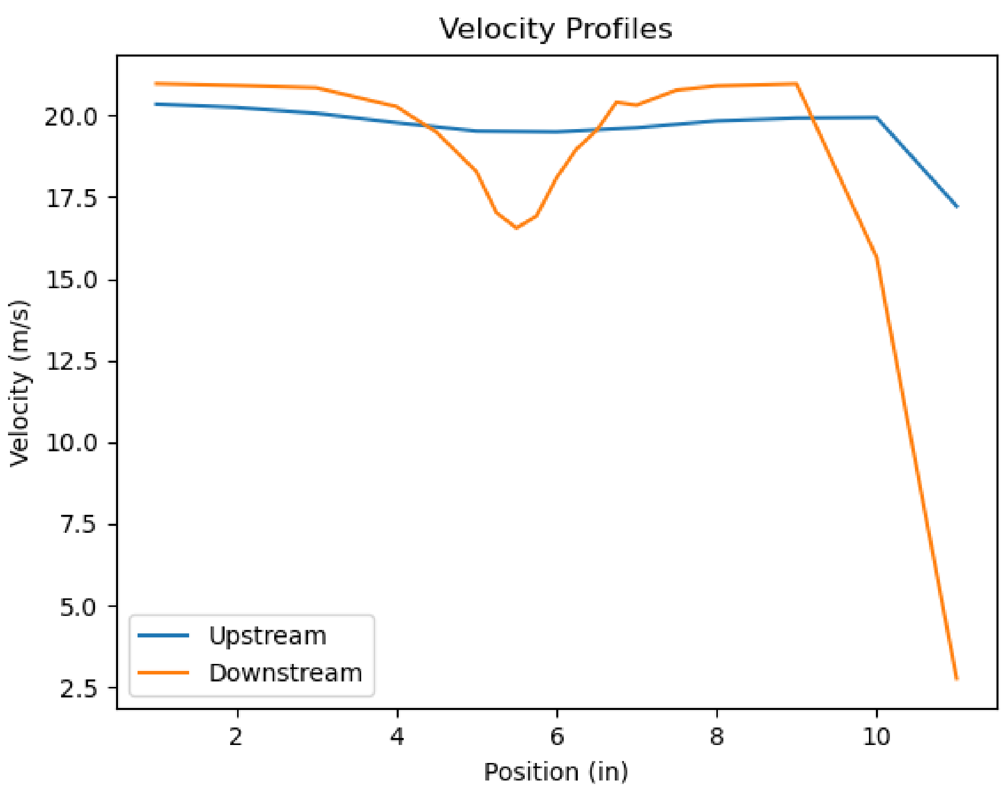
Upstream Velocity Sample Calculation

Given $P_{dyn}$ = 255.5 Pa

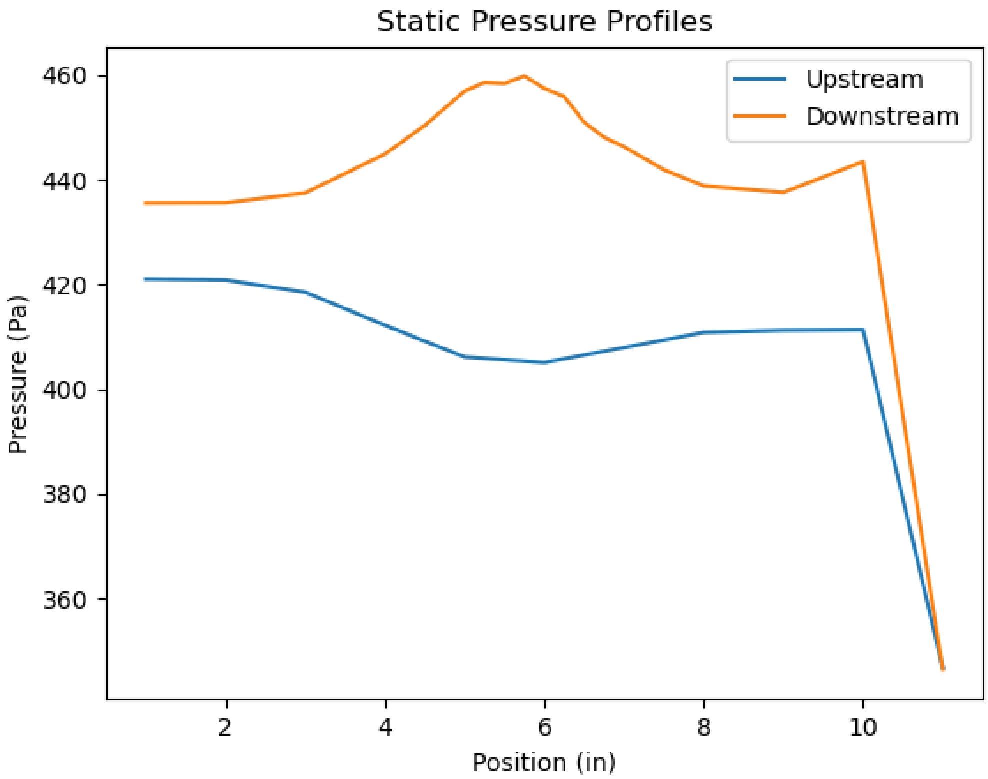
$P_{dyn}$ = ½ * (density) * $(\text{velocity})^2$

255.5 Pa = ½ * (1.225 $kg/m^3$) * $(\text{velocity})^2$

Velocity = 20.42 m/s



The negative gauge pressure (converted from a voltage using the linear fit) is then also mapped against the vertical position upstream and downstream of the cylinder.



<u>Control Volume Integration</u>

Positions and widths were converted to the metric system, velocity comes from velocities found for velocity profile graph. Absolute pressures are used in force from pressure integration, which is found from atmospheric pressure of 100.5 kPa minus gauge pressure. Force from pressure is found from the following:

$$\int_{y_{2,bot}}^{y_{2,top}} p_{0,2} w dy$$

Where ‘p’ was the average pressure between two positions, ‘w’ was the width, and ‘dy’ was the difference in height between two positions. The momentum flow integration was found from the following:

$$\int_{y_{2,bot}}^{y_{2,top}} \rho v_2^2 w dy$$

Where ‘p’ is the density of air, ‘v^2’ is the average squared velocity between two positions, ‘w’ was the width, and ‘dy’ was the difference in height between two positions. The last two positions were excluded from the control volume analysis due to the drag of the wind tunnel seen in the calculated velocities of 15.66 and 2.76 m/s at these positions.

| | | upstream CV | | | | |
|---|---|---|---|---|---|---|
| position (m) | width (m) | velocity (m/s) | gauge pressure (Pa) | absolute pressure (Pa) | momentum flow in (kg*m/s^2) | pressure force (kg*m/s^2) |
| 0.0254 | 0.3048 | 20.34938224 | 421.030008254117 | 100078.97 | 3.9075348599815 | 774.80401495 |
| 0.0508 | 0.3048 | 20.24703075 | 420.865814652602 | 100079.134 | 3.8535099765654 | 774.81354875 |
| 0.0762 | 0.3048 | 20.067494416 | 418.567104231395 | 100081.433 | 3.7651634025083 | 774.84691706 |
| 0.1016 | 0.3048 | 19.781590096 | 412.245650573077 | 100087.754 | 3.6628339174495 | 774.89490387 |
| 0.127 | 0.3048 | 19.522412804 | 406.17048731703 | 100093.83 | 3.6100802077607 | 774.9225519 |
| 0.1524 | 0.3048 | 19.498367945 | 405.103228907184 | 100094.897 | 3.6291478136723 | 774.91556044 |
| 0.1778 | 0.3048 | 19.625128521 | 407.976616933693 | 100092.023 | 3.6920709131806 | 774.8933149 |
| 0.2032 | 0.3048 | 19.835722226 | 410.850004960201 | 100089.15 | 3.7480025571879 | 774.88060316 |
| 0.2286 | 0.3048 | 19.92337325 | 411.260488963988 | 100088.74 | ignore b/c drag from tunnel | |
| 0.254 | 0.3048 | 19.940185045 | 411.342585764746 | 100088.657 | ignore b/c drag from tunnel | |
| 0.2794 | 0.3048 | 17.224464521 | 346.732403568684 | 100153.268 | | |
| | | | | Force (N): | 29.868343648306 | 6198.971415 |

| | downstream CV | | | | | | |
|---|---|---|---|---|---|---|---|
| position (in) | position (m) | width (m) | velocity (m/s) | gauge pressure (Pa) | absolute pressure (Pa) | momentum flow out (kg*m/s^2) | pressure force (kg*m/s^2) |
| 1 | 0.0254 | 0.3048 | 20.975371916 | 435.60219 | 100064.39781 | 4.161610708753 | 774.6904037935 |
| 2 | 0.0508 | 0.3048 | 20.920184345 | 435.643239 | 100064.35676 | 4.136822821068 | 774.6830150962 |
| 3 | 0.0762 | 0.3048 | 20.850391816 | 437.510941 | 100062.48906 | 4.010499931904 | 774.6469455417 |
| 4 | 0.1016 | 0.3048 | 20.273493506 | 444.961226 | 100055.03877 | 1.875272452321 | 387.2985180416 |
| 4.5 | 0.1143 | 0.3048 | 19.491492537 | 450.404244 | 100049.59576 | 1.693295988403 | 387.2752396727 |
| 5 | 0.127 | 0.3048 | 18.282844621 | 456.988407 | 100043.01159 | 0.739968711544 | 193.6296591109 |
| 5.25 | 0.13335 | 0.3048 | 17.027334936 | 458.630343 | 100041.36966 | 0.668643948181 | 193.6282608198 |
| 5.5 | 0.1397 | 0.3048 | 16.555880544 | 458.433311 | 100041.56669 | 0.664353736851 | 193.6270690944 |
| 5.75 | 0.14605 | 0.3048 | 16.920732077 | 459.861795 | 100040.1382 | 0.727157663822 | 193.6279509712 |
| 6 | 0.1524 | 0.3048 | 18.08520801 | 457.522036 | 100042.47796 | 0.814511133405 | 193.6317247682 |
| 6.25 | 0.15875 | 0.3048 | 18.973593263 | 455.962197 | 100044.0378 | 0.879460166041 | 193.6380011885 |
| 6.5 | 0.1651 | 0.3048 | 19.541284437 | 451.036389 | 100048.96361 | 0.946315959268 | 193.6455487825 |
| 6.75 | 0.17145 | 0.3048 | 20.405703053 | 448.163001 | 100051.837 | 0.983021100648 | 193.6500574768 |
| 7 | 0.1778 | 0.3048 | 20.318071253 | 446.377395 | 100053.6226 | 2.002389825065 | 387.3121116556 |
| 7.5 | 0.1905 | 0.3048 | 20.777945954 | 441.964692 | 100058.03531 | 2.059878656889 | 387.3266268706 |
| 8 | 0.2032 | 0.3048 | 20.906244479 | 438.877853 | 100061.12215 | 4.157701849542 | 774.6700173448 |
| 9 | 0.2286 | 0.3048 | 20.96962 | 437.634086 | 100062.36591 | ignore b/c drag from tunnel | |
| 10 | 0.254 | 0.3048 | 15.65712274 | 443.508112 | 100056.49189 | ignore b/c drag from tunnel | |
| 11 | 0.2794 | 0.3048 | 2.7569752763 | 346.445065 | 100153.55494 | | |
| | | | | | Force (N): | 30.52090465371 | 6196.981150229 |

Control Volume Sample Drag Calculation

$$\frac{\partial}{\partial t}\int_{CV} V\rho dV' + \int_{CS} V\rho \bar{V}\bar{n}dA = \sum \vec{F}$$

*CV integral is 0 because system is steady state - assuming no body forces & inviscid flow*

$$F_D = \left[\int_{y_{1,bot}}^{y_{1,top}} \rho v_1^2 w dy - \int_{y_{2,bot}}^{y_{2,top}} \rho v_2^2 w dy\right] + \left[\int_{y_{1,bot}}^{y_{1,top}} p_{0,1} w dy - \int_{y_{2,bot}}^{y_{2,top}} p_{0,2} w dy\right]$$

0 + (total momentum flow delta) = (drag force) - (total force from pressure delta)
(drag force) = (total momentum flow delta) + (total force from pressure delta)
= (29.868 - 30.521) + (6198.971 - 6196.981)
Drag = **1.338 N**

Using the same $C_D$ function as defined above, yields the following for the CV:

$C_D$ = **1.005**

Which, when compared against the given $C_D$ vs Reynolds' number graph, is almost exactly what should be expected for Reynolds' number for 20 m/s of $5 * 10^5$.

Python Plotting & Calculation Code:

```
import numpy as np
import matplotlib.pyplot as plt
import json
import csv
from math import cos, pi, radians, sqrt

def main():
   global density
   density = 1.225 # air density

   global lab_data
   lab_data = json.load(open("lab_data.json","r+"))

   global voltage_to_pressure_func
   voltage_to_pressure_func = step_1(plot = True)

   # surface pressure analysis
```

```
    slow_pressure_list, fast_pressure_list = step_2(plot = True)
    step_3(slow_pressure_list, fast_pressure_list, plot = True)

    slow_drag, fast_drag = 0.415, 1.763 # get values from spreadsheet

    # control volume analysis
    slow_cd = cd(slow_drag, "slow_speed")
    fast_cd = cd(fast_drag, "fast_speed")
    print(slow_cd, fast_cd)

    up_v, down_v = step_4(plot = True)
    up_p, down_p = step_5(plot = True)

    # up_v, up_p, down_v, and down_p to be used in spreadsheet to integrate
    cv_drag = 1.3377 # get values from spreadsheet

    cv_fast_cd = cd(cv_drag, "fast_speed")
    print(cv_fast_cd)

# linear fit of calibration data
def step_1(plot = False):
    # converts inH2O to pascals
    inH2O_to_Pa = lambda pressure_list: [x * 248.84 for x in pressure_list]

    y = inH2O_to_Pa(lab_data.get("manometer").get("manometer_height"))
    x = lab_data.get("manometer").get("voltage_readout")
    voltage_to_pressure_func = np.poly1d(np.polyfit(x, y, 1))

    if plot:
        plt.plot(x,y, 'yo', x, voltage_to_pressure_func(x), '--k')
        plt.ylabel("Pressure Reading (Pa)")
        plt.xlabel("Voltage Reading (V)")
        plt.show()

    return voltage_to_pressure_func

# show pressure distribution around cylinder for 2 different velocities
def step_2(plot = False):
    slow_volt = lab_data.get("slow_speed_voltage")
    fast_volt =  lab_data.get("fast_speed_voltage")
```

```
   slow_speed_data = [voltage_to_pressure_func(avg(lst)) for lst in
slow_volt]
   fast_speed_data = [voltage_to_pressure_func(avg(lst)) for lst in
fast_volt]
   theta = [i for i in range(0,190,15)]

   if plot:
       plt.plot(theta, slow_speed_data)
       plt.plot(theta, fast_speed_data)
       plt.ylabel("Pressure (Pa)")
       plt.xlabel("Angle (degrees)")
       plt.legend(["10 m/s", "20 m/s"])
       plt.title("Pressure Distribution")
       plt.show()

   return slow_speed_data, fast_speed_data

# show Cp distribution around cylinder for 2 different velocities
def step_3(slow_pressure_list, fast_pressure_list, plot = False):
   up_p = lab_data.get("upstream_pressures")
   def cp(data, speed):
       # Cp = (surface pressure - upstream static pressure) / (upstream
dynamic pressure)
       up_dyn_p =
voltage_to_pressure_func(up_p.get(speed).get("voltage_dyn"))
       up_stat_p =
voltage_to_pressure_func(up_p.get(speed).get("voltage_stat"))
       return (-data + up_stat_p) / up_dyn_p

   slow_cp_data = [cp(x, "slow_speed") for x in slow_pressure_list]
   fast_cp_data = [cp(x, "fast_speed") for x in fast_pressure_list]
   theta = [i for i in range(0,190,15)]

   if plot:
       plt.plot(theta, slow_cp_data)
       plt.plot(theta, fast_cp_data)
       plt.ylabel("Cp")
       plt.xlabel("Angle (degrees)")
       plt.legend(["10 m/s", "20 m/s"])
       plt.title("Pressure Distribution")
```

```
       plt.show()

# find velocity profiles up & downstream and plot them against position
def step_4(plot = False):
   # p = 1/2 * density * velocity ^ 2 (pressure to velocity func)
   p_to_vel = lambda pressure : sqrt(pressure * 2 / density)

   up_voltages = [avg(data) for data in
lab_data.get("upstream_cv").get("p_dyn")]
   down_voltages = [avg(data) for data in
lab_data.get("downstream_cv").get("p_dyn")]
   up_velocities = [p_to_vel(voltage_to_pressure_func(volt)) for volt in
up_voltages]
   down_velocities = [p_to_vel(voltage_to_pressure_func(volt)) for volt in
down_voltages]

   if plot:
       plt.plot(lab_data.get("upstream_cv").get("positions"),
up_velocities)
       plt.plot(lab_data.get("downstream_cv").get("positions"),
down_velocities)
       plt.ylabel("Velocity (m/s)")
       plt.xlabel("Position (in)")
       plt.legend(["Upstream", "Downstream"])
       plt.title("Velocity Profiles")
       plt.show()

   return up_velocities, down_velocities

# plot position against static pressure
def step_5(plot = False):
   up_voltages = [avg(data) for data in
lab_data.get("upstream_cv").get("p_static")]
   down_voltages = [avg(data) for data in
lab_data.get("downstream_cv").get("p_static")]
   up_pressures = [voltage_to_pressure_func(volt) for volt in up_voltages]
   down_pressures = [voltage_to_pressure_func(volt) for volt in
down_voltages]

   if plot:
```

```
       plt.plot(lab_data.get("upstream_cv").get("positions"),
up_pressures)
       plt.plot(lab_data.get("downstream_cv").get("positions"),
down_pressures)
       plt.ylabel("Pressure (Pa)")
       plt.xlabel("Position (in)")
       plt.legend(["Upstream", "Downstream"])
       plt.title("Static Pressure Profiles")
       plt.show()
   return up_pressures, down_pressures

# # # helper functions # # #

# Cd = drag/(dynamic_pressure * Area)
def cd(drag, speed):
   dynamic_voltage =
lab_data.get("upstream_pressures").get(speed).get("voltage_dyn")
   area = lab_data.get("cylinder_data").get("length") *
lab_data.get("cylinder_data").get("diameter")
   return drag / (voltage_to_pressure_func(dynamic_voltage) * area)

avg = lambda a_list: sum(a_list)/len(a_list)

# # # # # #

if __name__ == "__main__":
   main()
```

<u>Data JSON File:</u>

```
{
   "manometer":
   {
       "manometer_height":[0,0.5,1.0,1.5,2.0,2.5,3.0,3.5,4.0,4.5,5.0],

"voltage_readout":[-0.03,0.485,0.988,1.710,2.012,2.502,3.018,3.525,4.046,4
.550,5.054]
   },
   "slow_speed_voltage":
   [
```

```
        [0.255, 0.254, 0.256],
        [0.293, 0.294, 0.292],
        [0.426],
        [0.610, 0.607, 0.610, 0.600, 0.603],
        [0.782, 0.770, 0.775, 0.771, 0.774],
        [0.811, 0.802, 0.832, 0.811, 0.814, 0.820],
        [0.772, 0.762, 0.763, 0.781, 0.765, 0.766],
        [0.772, 0.750, 0.774, 0.768, 0.762, 0.748, 0.767],
        [0.779, 0.775, 0.769, 0.754, 0.753],
        [0.763, 0.757, 0.768, 0.758, 0.766, 0.752],
        [0.784, 0.787, 0.763, 0.793, 0.770],
        [0.767, 0.751, 0.780, 0.750, 0.775, 0.772],
        [0.879, 0.757, 0.751, 0.767, 0.781, 0.783]
    ],
    "fast_speed_voltage":
    [
        [0.702, 0.699, 0.701, 0.700, 0.697],
        [0.844, 0.847, 0.843, 0.841, 0.848, 0.845],
        [1.389, 1.382, 1.385, 1.380, 1.390, 1.385, 1.395],
        [2.133, 2.135, 2.141, 2.133, 2.154, 2.129, 2.130],
        [2.785, 2.763, 2.805, 2.799, 2.785],
        [2.957, 2.983, 2.976, 2.953, 2.998],
        [2.810, 2.816, 2.848, 2.803, 2.789, 2.870],
        [2.805, 2.781, 2.756, 2.784, 2.771, 2.734],
        [2.774, 2.813, 2.754, 2.764, 2.800],
        [2.868, 2.837, 2.832, 2.861, 2.823, 2.861],
        [2.947, 2.784, 2.893, 2.897, 2.848, 2.795],
        [2.862, 2.884, 2.902, 2.803, 2.903, 2.763],
        [2.918, 2.913, 2.832, 2.922, 2.889]
    ],
    "upstream_pressures":
    {

        "slow_speed":
        {
            "voltage_dyn":0.236,
            "voltage_stat":0.492
        },
        "fast_speed":
        {
```

```
            "voltage_dyn":0.940,
            "voltage_stat":1.640
        }
    },
    "cylinder_data":
    {
        "length":0.3048,
        "diameter":0.019,
        "note":"IN METERS"
    },
    "upstream_cv":
    {
        "positions":[1,2,3,4,5,6,7,8,9,10,11],
        "p_static":
        [
            [1.719, 1.717, 1.713],
            [1.713, 1.720, 1.714],
            [1.711, 1.709, 1.699],
            [1.680, 1.684, 1.678],
            [1.657, 1.654, 1.657],
            [1.654, 1.653, 1.648],
            [1.663, 1.662, 1.665],
            [1.675, 1.675, 1.675],
            [1.675, 1.677, 1.678],
            [1.676, 1.677, 1.678],
            [1.419, 1.412, 1.413]
        ],
        "p_dyn":
        [
            [1.035, 1.038, 1.037],
            [1.026, 1.027, 1.026],
            [1.012, 1.004, 1.009],
            [0.980, 0.978, 0.982],
            [0.958, 0.954, 0.952],
            [0.952, 0.953, 0.952],
            [0.963, 0.965, 0.966],
            [0.983, 0.985, 0.988],
            [0.994, 0.995, 0.993],
            [0.997, 0.996, 0.994],
            [0.745, 0.742, 0.747]
```

```
        ]
    },
    "downstream_cv":
    {

"positions":[1,2,3,4,4.5,5,5.25,5.5,5.75,6,6.25,6.5,6.75,7,7.5,8,9,10,11],
        "p_static":
        [
            [1.774, 1.780, 1.773, 1.775],
            [1.779, 1.776, 1.772],
            [1.781, 1.787, 1.781, 1.784],
            [1.806, 1.824, 1.810, 1.814],
            [1.832, 1.847, 1.831, 1.828, 1.840],
            [1.858, 1.870, 1.860, 1.856, 1.868, 1.862],
            [1.889, 1.864, 1.866, 1.867, 1.859],
            [1.866, 1.855, 1.863, 1.882, 1.875],
            [1.873, 1.869, 1.883, 1.871],
            [1.861, 1.870, 1.860, 1.854, 1.876, 1.866],
            [1.853, 1.846, 1.849, 1.864, 1.869, 1.868],
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            [1.417, 1.416, 1.408, 1.413]
        ],
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            [0.962, 0.942, 0.974, 0.962, 0.929, 0.941],
            [0.840, 0.879, 0.807, 0.893, 0.826, 0.756, 0.864, 0.840],
            [0.690, 0.770, 0.731, 0.673, 0.789, 0.707, 0.733, 0.730],
            [0.679, 0.652, 0.708, 0.680, 0.704, 0.639, 0.666, 0.780],
            [0.651, 0.722, 0.785, 0.747, 0.686, 0.674, 0.836, 0.650],
            [0.753, 0.808, 0.793, 0.884, 0.835, 0.784, 0.812, 0.893],
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            [0.998, 1.032, 0.982, 0.997, 1.306, 1.001, 1.022, 1.001],
            [1.026, 1.021, 1.038, 1.041, 1.035, 1.040],
            [1.081, 1.069, 1.083, 1.077, 1.082, 1.091],
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            [1.095, 1.104, 1.102, 1.103, 1.098],
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            [0.022, 0.043, 0.025, 0.013]
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    }
}
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