ENAE464 - 0202

Lab02: Pressure Drag and Lift on an Airfoil Model

Due on February 27th, 2026 at 11:59 PM

Dr. Silbaugh, 02:00 PM

Mikołaj Kostrzewa & Vai Srivastava

Experiment Performed: February 20th, 2026
Report Submitted: February 27th, 2026

February 27th, 2026

Enclosed is the technical report for the *Pressure Drag and Lift on an Airfoil Model* laboratory experiment. This report presents the experimental methodology, results, and analysis of aerodynamic characteristics observed on the surface of a scale model of a NACA airfoil, including lift coefficient and drag coefficient distributions, aerodynamic force analyses, and comparison with published NACA data.
Please feel free to contact us with any questions regarding the contents of this report.

Respectfully,
Mikołaj Kostrzewa & Vai Srivastava

Contents

Figures

Tables

Listings

1 Abstract

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2 Introduction

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3 Experimental Apparatus and Procedures

3.1 Experimental Apparatus

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3.2 Operating Technique

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4 Results

4.1 Operating Conditions

Table 4.1.1: Ambient Room Conditions during Experiment

Quantity	Value	Uncertainty
Room Temperature, T	$25\,^\circ\mathrm{C}$	$\pm 0.5\,^\circ\mathrm{C}$
Room Pressure, P	$1009.0\,\mathrm{hPa}$	$\pm 0.05\,\mathrm{hPa}$

The density of air (ρ) can be calculated using the Ideal Gas Law:

$$\rho = \frac{P}{RT} \tag{4.1.1}$$

where:

- P is the absolute pressure (in SI units: Pascals Pa)
- T is the absolute temperature (in Kelvin K)
- R is the specific gas constant for dry air, $R = 287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}$

Given measurements:

$$P = 1009.0\,\mathrm{hPa} = 100\,900\,\mathrm{Pa} \tag{4.1.2}$$

$$T = 25\,\mathrm{C} = 25 + 273.15 = 298.15\,\mathrm{K} \tag{4.1.3}$$

$$R = 287.05\,\frac{\mathrm{J}}{\mathrm{kg\,K}} \tag{4.1.4}$$

$$\rho = \frac{100\,900\,\mathrm{Pa}}{287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}} \times 298.15\,\mathrm{K} \tag{4.1.5}$$

Calculate:

$$\rho = \frac{100900}{287.05 \times 298.15} \tag{4.1.6}$$

$$= \frac{100900}{85542.5} \tag{4.1.7}$$

$$\approx 1.18\,\frac{\mathrm{kg}}{\mathrm{m^3}} \tag{4.1.8}$$

Thus, **the ambient air density during the experiment is**:

$$\boxed{\rho = 1.18\,\frac{\mathrm{kg}}{\mathrm{m^3}}} \tag{4.1.9}$$

4.2 Measurements

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4.3 Quantities of Interest

4.3.1 Incoming Wind Tunnel Airflow

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4.3.2 Coefficient of Pressure

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4.3.3 Pressure Drag and Lift Force

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4.3.4 Coefficient of Lift

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4.3.5 Coefficient of Drag

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5 Analysis and Discussion

5.1 Experimental Aerodynamic Characteristics vs. Published NACA Data

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5.2 Experimental Lift Curve vs. Published NACA Data

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5.3 Experimental Drag Polar vs. Published NACA Data

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6 Summary and Conclusions

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8 Appendices

8.1 Data

Table 8.1.1: Raw Measurements of Pressure Taps vs. Angle of Attack

`./data/pressure_taps_vs_aoa.csv`

```
AoA, Channel 1, Channel 2, Channel 3, Channel 4, Channel 5, Channel 6, Channel 7, Channel 8, Channel 9, Channel 10, Channel 11, Channel 12, Channel 13, Channel 14, Channel 15, Channel 16
-20, -69.206436, -886.344971, -851.163147, -788.391968, -639.438721, -674.0448, -545.104919, -455.617615, -817.457642, -919.410156, -917.260193, -931.250916, -915.066284, -917.640259, -924.629456, -701.653625
-18, -69.603416, -882.826111, -854.786499, -802.204224, -657.729126, -692.203796, -564.708801, -474.265839, -769.434509, -917.917847, -909.879089, -919.090088, -900.592102, -895.604675, -912.701416, -701.046265
-16, -69.735741, -876.179016, -865.009338, -825.352478, -684.256409, -727.949585, -600.341919, -502.057648, -688.143372, -895.648071, -892.579407, -907.257996, -891.658875, -885.664734, -900.205261, -704.690308
-14, -69.471085, -861.451416, -855.433472, -827.526611, -692.366272, -740.803284, -627.09552, -526.480774, -650.031555, -877.166443, -872.281311, -894.111145, -872.887756, -882.670776, -890.435547, -707.48407
-12, -69.471085, -852.849426, -857.245178, -835.967346, -704.826782, -763.572937, -647.04541, -549.219543, -604.146973, -883.480042, -887.158936, -896.302307, -884.421753, -886.622742, -881.006714, -711.249634
-10, -69.868073, -827.043518, -840.810913, -837.118408, -712.206299, -769.693848, -658.807739, -561.731873, -602.893311, -905.29071, -914.146301, -929.717102, -914.387939, -905.664368, -881.1203, -714.164734
-8, -69.338768, -781.817993, -810.918762, -817.423279, -696.600464, -768.714478, -663.881714, -566.544373, -611.9198, -958.669312, -951.052124, -956.01062, -924.338806, -893.449097, -836.36145, -719.266479
```

```
-6, -69.338768, -790.680664, -823.341492, -839.164673, -725.997559, -803.113708, -703.976379, -602.036072, -647.022705, -1142.911865, -838.143433, -806.465759, -767.384766, -740.996155, -722.64679, -720.359741
-4, -69.603416, -825.349243, -855.562866, -885.972595, -781.283508, -876.196716, -790.948059, -697.061523, -480.65976, -887.038574, -841.026672, -762.204834, -737.758057, -715.248047, -699.358582, -712.342773
-2, -69.471085, -854.283081, -871.738403, -919.991577, -820.11676, -933.855286, -876.999329, -807.10968, -429.760468, -809.553406, -758.565247, -743.251526, -717.969238, -698.122498, -689.475281, -708.33429
0, -68.941788, -794.851318, -898.654114, -947.871765, -857.740173, -984.53595, -945.909546, -900.596619, -435.276642, -753.534546, -724.081421, -721.230591, -701.911987, -687.940369, -683.784668, -707.605469
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8, -68.941788, -799.803955, -917.417725, -1053.765259, -1006.298462, -1205.25415, -1351.202271, -1476.511597, -1122.104004, -540.17395, -588.078613, -616.891052, -614.10022, -628.39093, -640.98407, -686.950623
10, -70.000397, -791.592957, -874.455811, -1023.199463, -995.047668, -1213.700806, -1282.292114, -1607.751831, -1283.931763, -523.724915, -569.000183, -606.680969, -605.599365, -629.591492, -653.050232, -693.150818
12, -69.471085, -817.398987, -834.08197, -963.218689, -949.802673, -1197.052124, -1260.434082, -1714.813354, -1443.235474, -510.036499, -557.784363, -593.067383, -604.692627, -629.951721, -649.749146, -686.950623
14, -68.941788, -844.768799, -861.386108, -906.051514, -886.411438, -1153.594116, -1284.937988, -1806.476929, -1602.182495, -494.852722, -553.04364, -587.578064, -596.985168, -623.588562, -656.123657, -685.002258
16, -69.338768, -956.724792, -965.296875, -949.022766, -818.181091, -957.359375, -949.360779, -949.920288, -788.693726, -551.216736, -592.24115, -626.881653, -633.028748, -658.405762, -697.313782, -674.164001
18, -69.471085, -976.926514, -956.368042, -943.523499, -821.326416, -961.521606, -957.413757, -954.240601, -830.088745, -527.06073, -574.897156, -610.08429, -617.727173, -658.16571, -696.177734, -669.658203
20, -69.338768, -970.670471, -971.249451, -956.184692, -832.214233, -959.562866, -956.493286, -960.96106, -877.986633, -501.294342, -554.084229, -595.812073, -612.853455, -646.279785, -688.565552, -664.665283
```

Table 8.1.2: NACA 4412 Airfoil Coordinates and the Corresponding Tap Locations on the Model Airfoil [1]

`./data/naca_4412_airfoil_coords_and_taps.csv`

x/c	y/c	Tap #	DSA Channel #
1	0	–	01
0.95	0.0147	–	–
0.90	0.0271	–	–
0.80	0.0489	01	02
0.70	0.0669	–	–
0.60	0.0814	02	03
0.50	0.0919	–	–
0.40	0.0980	03	04
0.30	0.0976	04	05
0.25	0.0941	–	–
0.20	0.0880	05	06
0.15	0.0789	–	–
0.10	0.0659	06	07
0.075	0.0576	–	–
0.05	0.0473	07	08
0.025	0.0339	–	–
0.0125	0.0244	–	–
0	0	08	09
0.0125	-0.0143	–	–
0.025	-0.0195	–	–
0.05	-0.0249	09	10
0.075	-0.0274	–	–
0.10	-0.0286	–	–
0.15	-0.0288	10	11
0.20	-0.0274	–	–
0.25	-0.0250	11	12
0.30	-0.0226	–	–
0.35	-0.0203	12	13
0.40	-0.0180	–	–
0.50	-0.0140	13	14
0.60	-0.0100	–	–
0.65	-0.00825	14	15
0.70	-0.0065	–	–
0.80	-0.0039	–	–
0.90	-0.0022	–	–
0.95	-0.0016	–	–
1	0	–	16

Table 8.1.3: NACA 4412 Airfoil Drag Polar [2]

`./data/xf-naca4412-il-1000000.csv`

```
Xfoil polar. Reynolds number fixed. Mach  number fixed
Polar key,xf-naca4412-il-1000000
Airfoil,naca4412-il
Reynolds number,1000000
Ncrit,9
Mach,0
Max Cl/Cd,129.373
Max Cl/Cd alpha,5.25
Url,http://www.airfoiltools.com/polar/csv?polar=xf-naca4412-il-1000000
```

α	C_l	C_d	C_{dp}	C_m	Top_{Xtr}	Bot_{Xtr}
-15.750	-0.8374	0.08373	0.08141	-0.0585	1.0000	0.0169
-15.500	-0.9127	0.06837	0.06591	-0.0687	1.0000	0.0166
-15.250	-1.0965	0.03328	0.03022	-0.0993	1.0000	0.0153
-15.000	-1.1161	0.03120	0.02803	-0.0956	1.0000	0.0154
-14.750	-1.1210	0.02977	0.02651	-0.0926	1.0000	0.0156
-14.500	-1.1215	0.02857	0.02523	-0.0896	1.0000	0.0159
-14.250	-1.1181	0.02751	0.02407	-0.0870	1.0000	0.0162
-14.000	-1.0990	0.02637	0.02282	-0.0871	0.9992	0.0166
-13.750	-1.0711	0.02533	0.02165	-0.0885	0.9979	0.0170
-13.500	-1.0462	0.02365	0.01985	-0.0903	0.9963	0.0177
-13.250	-1.0163	0.02288	0.01905	-0.0918	0.9951	0.0183
-13.000	-0.9847	0.02237	0.01850	-0.0933	0.9943	0.0189
-12.750	-0.9549	0.02183	0.01790	-0.0943	0.9930	0.0195
-12.500	-0.9260	0.02126	0.01724	-0.0952	0.9911	0.0201
-12.250	-0.8954	0.02078	0.01666	-0.0963	0.9894	0.0206
-12.000	-0.8682	0.01946	0.01525	-0.0976	0.9877	0.0214
-11.750	-0.8365	0.01894	0.01471	-0.0990	0.9866	0.0220
-11.500	-0.8038	0.01852	0.01424	-0.1004	0.9857	0.0227
-11.250	-0.7707	0.01808	0.01375	-0.1019	0.9849	0.0235
-11.000	-0.7369	0.01769	0.01328	-0.1035	0.9843	0.0242
-10.750	-0.7070	0.01745	0.01297	-0.1041	0.9819	0.0246
-10.500	-0.6803	0.01619	0.01161	-0.1049	0.9793	0.0257
-10.250	-0.6491	0.01569	0.01109	-0.1060	0.9775	0.0264
-10.000	-0.6172	0.01529	0.01065	-0.1071	0.9759	0.0271
-9.750	-0.5850	0.01491	0.01022	-0.1082	0.9742	0.0279
-9.500	-0.5547	0.01456	0.00981	-0.1089	0.9718	0.0287
-9.250	-0.5287	0.01426	0.00944	-0.1085	0.9665	0.0292
-9.000	-0.5023	0.01345	0.00855	-0.1085	0.9622	0.0299
-8.750	-0.4769	0.01285	0.00791	-0.1082	0.9574	0.0309
-8.500	-0.4513	0.01249	0.00752	-0.1078	0.9519	0.0317
-8.250	-0.4243	0.01214	0.00713	-0.1076	0.9474	0.0324

-8.000	-0.3979	0.01184	0.00678	-0.1073	0.9422	0.0333
-7.750	-0.3715	0.01155	0.00644	-0.1070	0.9363	0.0340
-7.500	-0.3442	0.01127	0.00609	-0.1068	0.9313	0.0345
-7.250	-0.3183	0.01080	0.00556	-0.1064	0.9249	0.0354
-7.000	-0.2921	0.01033	0.00505	-0.1061	0.9186	0.0365
-6.750	-0.2649	0.01003	0.00471	-0.1059	0.9125	0.0375
-6.500	-0.2377	0.00977	0.00441	-0.1057	0.9053	0.0384
-6.000	-0.1825	0.00935	0.00389	-0.1054	0.8910	0.0404
-5.750	-0.1549	0.00912	0.00360	-0.1052	0.8835	0.0414
-5.500	-0.1275	0.00880	0.00325	-0.1051	0.8751	0.0435
-5.000	-0.0718	0.00845	0.00283	-0.1049	0.8578	0.0476
-4.750	-0.0441	0.00824	0.00259	-0.1047	0.8488	0.0519
-4.500	-0.0162	0.00810	0.00243	-0.1046	0.8388	0.0569
-4.250	0.0117	0.00793	0.00228	-0.1045	0.8288	0.0655
-4.000	0.0394	0.00780	0.00213	-0.1044	0.8184	0.0745
-3.750	0.0674	0.00769	0.00201	-0.1044	0.8073	0.0820
-3.500	0.0954	0.00761	0.00191	-0.1043	0.7964	0.0890
-3.250	0.1232	0.00752	0.00180	-0.1042	0.7851	0.0977
-3.000	0.1512	0.00745	0.00171	-0.1041	0.7733	0.1066
-2.750	0.1791	0.00737	0.00163	-0.1040	0.7616	0.1182
-2.500	0.2069	0.00729	0.00156	-0.1040	0.7497	0.1332
-2.250	0.2346	0.00723	0.00150	-0.1039	0.7378	0.1502
-2.000	0.2625	0.00715	0.00145	-0.1038	0.7254	0.1697
-1.750	0.2903	0.00709	0.00142	-0.1038	0.7132	0.1927
-1.500	0.3180	0.00703	0.00141	-0.1037	0.7012	0.2214
-1.250	0.3456	0.00701	0.00139	-0.1036	0.6886	0.2466
-1.000	0.3734	0.00697	0.00138	-0.1035	0.6754	0.2686
-0.750	0.4012	0.00694	0.00137	-0.1035	0.6626	0.2903
-0.500	0.4288	0.00691	0.00138	-0.1034	0.6497	0.3203
-0.250	0.4562	0.00686	0.00139	-0.1033	0.6365	0.3629
0.000	0.4833	0.00678	0.00141	-0.1032	0.6232	0.4192
0.250	0.5102	0.00658	0.00146	-0.1031	0.6101	0.5177
0.500	0.5366	0.00635	0.00153	-0.1029	0.5975	0.6393
0.750	0.5622	0.00617	0.00160	-0.1024	0.5856	0.7449
1.000	0.5842	0.00594	0.00170	-0.1009	0.5740	0.8717
1.250	0.6163	0.00588	0.00177	-0.1014	0.5622	0.9842
1.500	0.6525	0.00598	0.00181	-0.1033	0.5505	1.0000
1.750	0.6788	0.00611	0.00186	-0.1029	0.5398	1.0000
2.000	0.7055	0.00622	0.00192	-0.1026	0.5294	1.0000
2.250	0.7325	0.00633	0.00199	-0.1024	0.5204	1.0000
2.500	0.7592	0.00646	0.00206	-0.1022	0.5112	1.0000
2.750	0.7865	0.00656	0.00213	-0.1020	0.5029	1.0000
3.250	0.8405	0.00681	0.00231	-0.1016	0.4847	1.0000
3.500	0.8672	0.00696	0.00240	-0.1014	0.4746	1.0000
3.750	0.8941	0.00709	0.00250	-0.1012	0.4646	1.0000
4.000	0.9210	0.00722	0.00260	-0.1010	0.4540	1.0000
4.250	0.9473	0.00739	0.00272	-0.1007	0.4426	1.0000

4.500	0.9734	0.00758	0.00284	-0.1004	0.4273	1.0000
4.750	0.9993	0.00778	0.00297	-0.1001	0.4110	1.0000
5.000	1.0254	0.00797	0.00311	-0.0998	0.3979	1.0000
5.250	1.0518	0.00813	0.00326	-0.0995	0.3861	1.0000
5.500	1.0777	0.00834	0.00342	-0.0992	0.3731	1.0000
5.750	1.1031	0.00857	0.00359	-0.0988	0.3575	1.0000
6.000	1.1280	0.00884	0.00379	-0.0983	0.3398	1.0000
6.250	1.1523	0.00914	0.00401	-0.0978	0.3207	1.0000
6.500	1.1761	0.00948	0.00426	-0.0971	0.2993	1.0000
6.750	1.1988	0.00989	0.00455	-0.0963	0.2737	1.0000
7.000	1.2208	0.01036	0.00488	-0.0954	0.2461	1.0000
7.250	1.2417	0.01089	0.00526	-0.0943	0.2173	1.0000
7.500	1.2614	0.01149	0.00569	-0.0931	0.1865	1.0000
7.750	1.2793	0.01220	0.00621	-0.0915	0.1526	1.0000
8.000	1.2973	0.01288	0.00672	-0.0900	0.1252	1.0000
8.250	1.3164	0.01345	0.00719	-0.0887	0.1065	1.0000
8.500	1.3346	0.01404	0.00769	-0.0872	0.0893	1.0000
8.750	1.3514	0.01469	0.00823	-0.0854	0.0729	1.0000
9.000	1.3676	0.01527	0.00875	-0.0836	0.0622	1.0000
9.250	1.3835	0.01581	0.00926	-0.0817	0.0563	1.0000
9.500	1.4004	0.01631	0.00976	-0.0799	0.0521	1.0000
9.750	1.4171	0.01682	0.01028	-0.0782	0.0491	1.0000
10.000	1.4317	0.01746	0.01091	-0.0762	0.0459	1.0000
10.250	1.4484	0.01797	0.01147	-0.0746	0.0442	1.0000
10.500	1.4653	0.01849	0.01203	-0.0731	0.0427	1.0000
10.750	1.4805	0.01911	0.01267	-0.0714	0.0411	1.0000
11.000	1.4938	0.01986	0.01343	-0.0695	0.0392	1.0000
11.250	1.5061	0.02069	0.01430	-0.0676	0.0376	1.0000
11.500	1.5221	0.02129	0.01495	-0.0662	0.0368	1.0000
11.750	1.5369	0.02199	0.01570	-0.0647	0.0356	1.0000
12.000	1.5500	0.02282	0.01656	-0.0631	0.0343	1.0000
12.250	1.5608	0.02382	0.01758	-0.0614	0.0330	1.0000
12.500	1.5688	0.02506	0.01888	-0.0594	0.0316	1.0000
12.750	1.5831	0.02588	0.01975	-0.0582	0.0308	1.0000
13.000	1.5959	0.02683	0.02075	-0.0569	0.0298	1.0000
13.250	1.6066	0.02796	0.02192	-0.0555	0.0286	1.0000
13.500	1.6141	0.02939	0.02338	-0.0540	0.0273	1.0000
13.750	1.6213	0.03089	0.02494	-0.0526	0.0262	1.0000
14.000	1.6325	0.03209	0.02620	-0.0516	0.0252	1.0000
14.250	1.6414	0.03354	0.02770	-0.0505	0.0241	1.0000
14.500	1.6474	0.03528	0.02947	-0.0493	0.0229	1.0000
14.750	1.6508	0.03731	0.03156	-0.0482	0.0218	1.0000
15.000	1.6585	0.03899	0.03332	-0.0474	0.0209	1.0000
15.250	1.6638	0.04096	0.03533	-0.0466	0.0198	1.0000
15.500	1.6661	0.04330	0.03772	-0.0458	0.0187	1.0000
15.750	1.6666	0.04589	0.04037	-0.0451	0.0179	1.0000
16.000	1.6698	0.04827	0.04284	-0.0447	0.0171	1.0000

16.250	1.6706	0.05099	0.04562	-0.0443	0.0164	1.0000
16.500	1.6692	0.05402	0.04871	-0.0440	0.0157	1.0000
16.750	1.6638	0.05759	0.05235	-0.0439	0.0151	1.0000
17.000	1.6605	0.06101	0.05587	-0.0439	0.0146	1.0000
17.250	1.6584	0.06435	0.05931	-0.0441	0.0142	1.0000
17.500	1.6548	0.06793	0.06298	-0.0444	0.0138	1.0000
17.750	1.6497	0.07175	0.06689	-0.0448	0.0134	1.0000
18.000	1.6430	0.07583	0.07106	-0.0453	0.0131	1.0000
18.250	1.6346	0.08024	0.07555	-0.0461	0.0128	1.0000
18.500	1.6237	0.08507	0.08047	-0.0470	0.0124	1.0000
18.750	1.6097	0.09040	0.08590	-0.0482	0.0121	1.0000

8.2 Code

For the sake of brevity, only the code files that are key to the analysis are included below. However, in the spirit of completeness, the repository containing the complete data, source code, and notes for this report can be found at github:vaisriv/enae464-lab02.

Listing 8.2.1: Index File
`./src/index.py`

```python
import os
import sys
import csv
import numpy as np
import matplotlib.pyplot as plt

def main():
    # ── Physical constants & ambient conditions ──────────────────────────
    P_AMB     = 100900.0 # Ambient pressure [Pa]
    T_AMB     = 298.15   # Ambient temperature [K]
    RHO_AIR   = 1.18     # Air density [kg/m^3]
    RHO_WATER = 998.0    # Water density [kg/m^3]
    G         = 9.81     # Gravitational acceleration [m/s^2]

    # ── File paths ────────────────────────────────────────────────────────
    INPUT_CSV  = "./data/pressure_vs_theta.csv"
    OUTPUT_CSV = "./outputs/text/pressure_vs_theta.csv"
    OUTPUT_FILE = "./outputs/text/summary.txt"

    # ── Ensure figures output directory exists ────────────────────────────
    FIG_DIR = os.path.join("outputs", "figures")
    os.makedirs(FIG_DIR, exist_ok=True)

    # ── Read CSV ──────────────────────────────────────────────────────────
    theta_deg_list = []
    P_inf_raw_list = []
    P_0_raw_list   = []
```

```python
    P_raw_list     = []

    with open(INPUT_CSV, newline="") as f:
        reader = csv.DictReader(f)
        for row in reader:
            theta_deg_list.append(float(row["theta_deg"]))
            P_inf_raw_list.append(float(row["P_inf"]))
            P_0_raw_list.append(float(row["P_0"]))
            P_raw_list.append(float(row["P"]))

    N = len(theta_deg_list)
    print(f"Read {N} data points from '{INPUT_CSV}'.")

    # ── Convert water column heights to differential pressures ──────────────────
    # The manometer readings are heights (in cm of water):
    #     ΔP = ρ_water · g · Δh
    #     P_actual = P_ref - ρ_water · g · h_reading
    #     P_surface - P_freestream  =  ρ_water · g · (h_surface - h_inf)
    #     q_inf = P_0 - P_inf = ρ_water · g · (h_0 - h_inf)
    SCALE = 1e-2  # Measurements taken in cm (convert to meters)

    # ── Compute differential pressures ────────────────────────────────────────
    # For each data point we have a corresponding P_inf and P_0 reading,
    # so we compute per-row to account for any drift.
    delta_P_list = [] # P_surface - P_freestream  [Pa]
    q_inf_list   = [] # dynamic pressure  [Pa]
    U_inf_list   = [] # freestream velocity [m/s]
    Cp_list      = [] # pressure coefficient

    for i in range(N):
        h_inf = P_inf_raw_list[i] * SCALE # freestream static tap height [m]
        h_0   = P_0_raw_list[i]   * SCALE # stagnation tap height [m]
        h_p   = P_raw_list[i]     * SCALE # surface tap height [m]

        # (P_surface - P_inf) in Pa
        # Higher reading = higher pressure, so:
        delta_P = RHO_WATER * G * (h_p - h_inf)

        # Dynamic pressure  q = P_total - P_static = rho_w * g * (h_0 - h_inf)
        q_inf = RHO_WATER * G * (h_0 - h_inf)

        if q_inf <= 0:
            print(f"WARNING row {i}: q_inf = {q_inf:.2f} Pa <= 0  (h_inf={h_inf:.4f}, h_0={h_0:.4f})")
            # Use absolute value as fallback but flag it
            q_inf = abs(q_inf) if abs(q_inf) > 1e-6 else 1e-6

        U_inf = (2.0 * q_inf / RHO_AIR) ** 0.5 # Bernoulli: q = 0.5 * rho * U^2
```

```python

        Cp = delta_P / q_inf # Cp = (P - P_inf) / q_inf  = (P - P_inf) / (0.5 * rho * U^2)

        delta_P_list.append(delta_P)
        q_inf_list.append(q_inf)
        U_inf_list.append(U_inf)
        Cp_list.append(Cp)

    # ── Convert lists to numpy arrays for convenience ──────────────────────────
    theta_deg = np.array(theta_deg_list)
    theta_rad = np.deg2rad(theta_deg)
    Cp_exp    = np.array(Cp_list)
    dP_exp    = np.array(delta_P_list)
    q_inf_arr = np.array(q_inf_list)

    # ── Inviscid (potential flow) theory for a cylinder ─────────────────────────
    # Cp_inviscid = 1 - 4 sin^2(theta)
    theta_theory = np.linspace(0, 180, 500)
    theta_theory_rad = np.deg2rad(theta_theory)
    Cp_inviscid = 1.0 - 4.0 * np.sin(theta_theory_rad) ** 2

    # ── Figure 1: Cp vs theta ──────────────────────────────────────────────────
    fig1, ax1 = plt.subplots(figsize=(9, 5))
    ax1.plot(theta_deg, Cp_exp, 'o', markersize=5, label='Experimental')
    ax1.plot(theta_theory, Cp_inviscid, '-', linewidth=1.5, label='Inviscid theory ($1 -
    ↪  4\\sin^2\\theta$)')
    ax1.set_xlabel(r'$\theta$ [deg]')
    ax1.set_ylabel(r'$C_p$')
    ax1.set_title(r'Pressure Coefficient $C_p$ vs Angular Position $\theta$')
    ax1.legend()
    ax1.grid(True, alpha=0.3)
    fig1.tight_layout()
    fig1.savefig(os.path.join(FIG_DIR, "Cp_vs_theta.png"), dpi=300)
    print(f"Saved {os.path.join(FIG_DIR, 'Cp_vs_theta.png')}")

    # ── Figure 2: Cd vs theta (cumulative drag coefficient) ────────────────────
    #
    # The drag force on the cylinder (per unit span) is:
    #     D = R ∫₀²π P·cos(θ) dθ
    #
    # We define the drag coefficient as:
    #     C_d = D / (q_inf · d)  =  D / (q_inf · 2R)
    #
    # Substituting and non-dimensionalising with Cp = (P - P_inf) / q_inf :
    #     C_d = (1/2) ∫₀²π Cp · cos(θ) dθ
    #
    # (The P_inf contribution integrates to zero over a closed surface.)
    #
```

```
    # We approximate the integral cumulatively using the trapezoidal rule so we
    # can plot C_d as a function of the upper integration limit θ.

    # Sort by angle to ensure proper integration order
    sort_idx  = np.argsort(theta_deg)
    theta_sorted     = theta_deg[sort_idx]
    theta_sorted_rad = theta_rad[sort_idx]
    Cp_sorted        = Cp_exp[sort_idx]

    # Integrand: Cp(θ) · cos(θ)
    integrand_exp = Cp_sorted * np.cos(theta_sorted_rad)

    # Cumulative trapezoidal integration: (1/2) ∫₀^θ Cp·cos(θ') dθ'
    Cd_cumulative_exp = np.zeros(len(theta_sorted))
    for j in range(1, len(theta_sorted)):
        dtheta = theta_sorted_rad[j] - theta_sorted_rad[j - 1]
        Cd_cumulative_exp[j] = Cd_cumulative_exp[j - 1] + 0.5 * (integrand_exp[j] +
        ↪  integrand_exp[j - 1]) * dtheta
    Cd_cumulative_exp *= 0.5  # the 1/2 prefactor from C_d = (1/2) ∫ Cp cos(θ) dθ

    # Inviscid theory: Cp_inv = 1 - 4sin²θ  →  Cd = 0 (d'Alembert's paradox)
    # Cumulative for plotting:
    integrand_inv = (1.0 - 4.0 * np.sin(theta_theory_rad) ** 2) * np.cos(theta_theory_rad)
    Cd_cumulative_inv = np.zeros(len(theta_theory))
    for j in range(1, len(theta_theory)):
        dtheta = theta_theory_rad[j] - theta_theory_rad[j - 1]
        Cd_cumulative_inv[j] = Cd_cumulative_inv[j - 1] + 0.5 * (integrand_inv[j] +
        ↪  integrand_inv[j - 1]) * dtheta
    Cd_cumulative_inv *= 0.5

    fig2, ax2 = plt.subplots(figsize=(9, 5))
    ax2.plot(theta_sorted, Cd_cumulative_exp, 'o-', markersize=4, linewidth=1,
    ↪  label='Experimental (trapezoidal)')
    ax2.plot(theta_theory, Cd_cumulative_inv, '-', linewidth=1.5, label="Inviscid theory
    ↪  (d'Alembert: $C_d = 0$)")
    ax2.set_xlabel(r'$\theta$ [deg]')
    ax2.set_ylabel(r'$C_d(\theta)$  (cumulative)')
    ax2.set_title(r'Cumulative Drag Coefficient $C_d$ vs Angular Position $\theta$')
    ax2.legend()
    ax2.grid(True, alpha=0.3)
    fig2.tight_layout()
    fig2.savefig(os.path.join(FIG_DIR, "Cd_vs_theta.png"), dpi=300)
    print(f"Saved {os.path.join(FIG_DIR, 'Cd_vs_theta.png')}")

    # Print final Cd value (full integral over 0 to max angle)
    print(f"\nExperimental C_d (integrated 0 to {theta_sorted[-1]:.0f} deg):
    ↪  {Cd_cumulative_exp[-1]:.4f}")
```

```
    print(f"Inviscid theory C_d (integrated 0 to 360 deg):      {Cd_cumulative_inv[-1]:.6f} (≈ 0, d'Alembert's paradox)")

    # ── Summary statistics ──────────────────────────────────────
    q_avg   = sum(q_inf_list) / N
    U_avg   = sum(U_inf_list) / N

    with open(OUTPUT_FILE, "w", newline="") as f:
        f.write(f"Ambient conditions:")
        f.write(f"  P_amb   = {P_AMB} Pa")
        f.write(f"  T_amb   = {T_AMB} K")
        f.write(f"  rho_air = {RHO_AIR} kg/m^3")
        f.write(f"\nDerived quantities (averages over all rows):")
        f.write(f"  q_inf   = {q_avg:.2f} Pa")
        f.write(f"  U_inf   = {U_avg:.2f} m/s")

    print(f"\nSummary written to '{OUTPUT_FILE}'.")

    # ── Write output table ──────────────────────────────────────
    with open(OUTPUT_CSV, "w", newline="") as f:
        writer = csv.writer(f)
        writer.writerow(["theta_deg", "P-P_inf_Pa", "Cp", "P_Pa"])

        for i in range(N):
            # P_actual = P_amb + (P_surface - P_inf) i.e. ambient + differential
            P_actual = P_AMB + delta_P_list[i]
            writer.writerow([
                f"{theta_deg_list[i]:.1f}",
                f"{delta_P_list[i]:.3f}",
                f"{Cp_list[i]:.4f}",
                f"{P_actual:.3f}",
            ])

    print(f"\nResults written to '{OUTPUT_CSV}'.")


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