Applied Lunar and Planetary Aerodynamic Characteristic Analysis of Sondes (ALPACAS)

by

Jackson Dail Ritter and Will Harvey Mealer

An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

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April 24th, 2019

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Table of Contents

Abstract

The first phase of the experiment consisted of preliminary research to determine the range of Reynolds numbers that would be applicable to various planetary environments including Earth and Saturn. Two different sonde designs were then modeled and 3D printed to be tested in the UAH wind tunnel. The models were created in Solid Edge from existing models created by the ICEE Sonde team and were then processed using Ultimaker Cura to prepare the files for 3-D printing. After printing, the models were refined to give them a more smooth and even surface. The wind tunnel and a force gauge were used to determine the drag for different dynamic pressure values for each body. Calculations were made to determine the corresponding Reynolds number and drag coefficient for each data point. The data was then processed into graphs, analyzed, and compared to graphs of similar bodies to determine if the results aligned with published theory. The results were then further analyzed to determine which sonde design would be applicable various planetary environments. Ultimately, the coefficient of drag of design Bravo (a wide, open-faced cylinder) followed the expected results for a flat plate perpendicular to the flow, while design Alpha (a narrow, streamlined design with a short nose cone) had slightly larger drag coefficients than expected. Regardless, the results showed that because of the much smaller cross sectional area, design Alpha would be a more effective design to be used in planetary conditions where there is a significant effect from atmosphere, such as Saturn or Earth.

Introduction

The purpose of the ALPACAS project is to determine suitable shapes for sondes that will be used in various planetary conditions. This project stems from the senior design mission called the Interior and Composition for Enceladus Exploration (ICEE) mission. The purpose of this mission is to investigate the planetary structure of Enceladus (one of Saturn's moons) as well as to analyze the possibility of life existing on the moon. As part of this mission, The University of Alabama in Huntsville (UAH) team has designed a sonde to analyze various aspects of the moon's atmosphere such as chemical makeup, temperature, and pressure. A sonde is an atmospheric device used on Earth that typically measures the pressure, temperature, and density of the atmosphere at various altitudes to gain more comprehensive knowledge about weather patterns (see Fig. 1). As can be seen in the figure, a parachute and the sonde's own drag coefficient are critical to analyzing how long the device can stay in the air and take measurements, as the greater the drag the slower it falls. It is for this reason that the drag coefficient must be measured to ensure its efficacy and usefulness. The drag of the sonde will be measured in a wind tunnel at multiple Reynolds numbers in order to gain a better approximation of its drag coefficients in different conditions.

The chosen conditions of interest are those of Enceladus, Earth, and Saturn. The conditions of Enceladus are quite unusual, as Enceladus has an extremely thin, and cold, atmosphere and thus drag will not be as much of a concern as it is for a typical Earth sonde. Saturn is almost the opposite, it has an extremely odd atmosphere whose composition and pressure changes drastically between layers. While Earth's atmosphere was chosen as a baseline comparison, Saturn's was chosen for its interest and feasibility as a potential future mission for NASA. Sondes are extremely useful for analyzing the atmosphere of a planet and thus this project could prove useful in future missions not just to Enceladus, but to Saturn as well. Not only has there been no major research done on sondes being used in space, but there is also very little research even for those in use on Earth, particularly on their aerodynamic qualities.

The atmospheric information critical to this analysis is shown in Tables A3 and A4 in the Appendix. It should be noted that average values were used for the temperature and pressure for each layer as they can vary throughout. Furthermore, the density was calculated using the ideal gas law (Equation 5), hence the need for the individual gas constants. Unfortunately, the viscosity of the of these layers are unknown and a maximum and minimum viscosity value had to be selected from Ref. 2 for the various temperature ranges for each layer (see Ref. 1).

Design Overview

Design Alpha (pictured in Fig. A3) is the more aerodynamic of the two designs tested. It features a long and narrow body, with a protective nose. Channels behind the nose would be open to allow the atmosphere to flow into the sonde. The science instruments would be inside of the channel and would test the incoming particles. Design Bravo (pictured in Fig. A4), on the other hand, is short and wide without an open top instead of a protective nose. The atmosphere would flow directly into the sonde and the science instruments without any protection or diversion. Originally, the ICEE mission planned to use Alpha before it was replaced with the Bravo design. The lack of a substantial atmosphere on Enceladus rendered the improved aerodynamic qualities of Alpha over Bravo unimportant, while the direct access to the atmosphere of Bravo became crucial. The low density of atmosphere and the lack of large debris allowed for the instruments in Bravo to be open to the atmosphere without the normal risk of burning up or impacting on debris. In addition, the air in the channels of design Alpha would be at a different pressure from the outside atmosphere and would need correction. Thus Bravo was chosen due to the compact nature in a mission where space is limited as well as the fact that a nose is not needed to protect the instrumentation.

Both models Alpha and Bravo were designed using Solid Edge ST-10. A bracket was added to Bravo that allowed the model to be mounted to the force gauge in the wind tunnel. The bracket was placed on the back of the Bravo sonde and out of the main airstream, to prevent it from impacting the results. Both designs were saved as a .stl file and imported to Ultimaker Cura (a program used to prepare a design for 3-D printing). The channels in Alpha were removed to reduce the complexity of the design and increase the probability of a successful print. Due to limitations of the printer used, both models were printed at the same length of 4.5 inches, making Alpha a one-sixth scale model and Bravo a one-third scale model. PLA (polylactic acid) was the chosen material due to cost and ease of access. Alpha took twelve and a half hours to print while Bravo took just under twenty-three hours. The support bracket on Bravo initially experienced layer shifting (when the layers of the material do not stack evenly), but adjusting the print settings allowed for the rest of the model to be printed without issue. Since the main purpose of this experiment is to derive a drag coefficient for each model, the friction factor of the material itself needed to be consistent. The models were sanded with coarse 60 grit sandpaper to remove the ridges of each layer and a high fill primer spray paint was applied evenly to the models. After drying, both models were sanded with a fine 120 grit sandpaper to remove smaller imperfections.

A final coat of the high fill primer spray paint was applied, leaving the models smooth and ready for testing.

Testing

Testing began by mounting Alpha onto the force gauge (pictured in Fig. A3). The dynamic pressure was increased (which was later used to calculate the Reynold's number) in steady increments of ~0.25 inH2O. There is significant hysteresis and high sensitivity when changing the dynamic pressure, so the increments were not exact. In addition, the drag readings tended to oscillate around a given point. Due to the low precision of the sensors many data points had to be estimated from the few changing points shown on the display. Alpha tested smoothly with a small increase in drag over the entire experiment (from 0.0035 at a dynamic pressure of 0.1 inH2O to 0.0150 at a dynamic pressure of 4.002 inH2O). There were no complications in testing Alpha. See Table A1 for the Alpha testing data.

Bravo was significantly wider than Alpha, and the mounting apparatus used was not as effective. Bravo began to vibrate significantly early on in the testing with a dynamic pressure of 0.247 inches of water. The wind tunnel was turned off and testing began again within a smaller range with much smaller increments (from increments of ~0.25 inH2O originally to increments of ~.01 inH2O). The experiment continued in small increments until the vibration increased to a dangerous point at 0.391 inH2O. See table A2 for the Bravo testing data. The testing was then concluded, as further testing could have lead to the model breaking and damaging the wind tunnel.

Before the drag and dynamic pressure readings were recorded the initial drag, called the tare, was recorded and then subtracted from the recordings using Equation 1 in the Appendix. Once the drag was corrected, the lab's air density and dynamic viscosity were found from the recorded lab temperature and pressure values of 21℃ and 98900 Pa using Equations 2 and 3 and were determined to be 1.171 $\frac{kg}{m^3}$ and $1.818 * 10^{-5}$ Pa*s. With these two values and the cross-sectional area of the models, the air velocity, Reynolds number, and coefficient of drag could then be found from Equations 2, 3, and 6 respectively. It is important to note that the drag measured is actually the drag in units of kilograms, and that the dynamic pressure recorded is in units of inches of water, both of which must to be converted to SI units before calculations. Once the coefficients and Reynolds numbers were found, they were then plotted in Figures A1 and A2, while the tables and sample calculations showing this information are also in the Appendix in Tables A1 and A2 and in the Equations section respectively. As can be seen in the tables, the first data point recorded was a clear outlier for both designs and as such those data points were removed from all figures.

Conclusions

One challenge of particular note was the mounting of the models to the force gauge. Model Alpha was mounted without much difficulty, as the mounting rod could be inserted into the tail end of the sonde. Because the model was solid, it was therefore easy to attach it to the force gauge. Bravo, however, was difficult to mount due to the holes in the bottom that were designed to allow flow out of the back of the sonde. The wide nature of the model also made it difficult to test in the confined test section area. Unfortunately, Bravo was only attached to the force gauge at one point, which allowed vibrations to build up in the model that eventually led to having to shut down the test early. Our testing range then had to be modified for Bravo, as it could only get to a Reynolds number of approximately 90,000 before the vibrations got too severe to continue testing. Although it was then too late to make a better attachment, the testing increments were decreased and Bravo was tested from a Reynolds number of 34,600 to 90,000. Vibration began at a Reynold's number of 70,000 and the model was observed carefully with small increases of the Reynold's number until it reached 90,000. The experimental range was cut short to ensure the safety of the lab equipment. If the experiment was not stopped, the model could have broken apart and damaged the wind tunnel.

Another difficulty was approximating the viscosity of the atmosphere of Saturn and Enceladus. This was particularly difficult because the atmospheres of these environments are not known to great detail and finding the chemical properties (such as the viscosity) are not well known for the chemicals that make up their atmospheres. As stated previously, maximum and minimum viscosities thus had to be approximated from Ref. 2. These numbers were then used to determine the approximate Reynolds numbers that would be experienced in the various environments of interest (see Tables A3 and A4). The descent speed used to find these numbers was assumed to match that of Earth-based sondes that was given in Ref. 1.

The project confirmed that Bravo would not be practical in an environment with a substantial atmosphere. While it would work well in the low density atmosphere of Enceladus, Bravo would experience considerable drag entering denser atmospheres. The high coefficient of drag along with the sizable cross sectional area means that the atmosphere would burn up or disintegrate Bravo and the unprotected instruments that it carries if it were to be used on either

Earth or Saturn. In these testing environments Alpha, or another sonde of similar characteristics, would be more efficient and effective. This is seen when the drag of the two sondes were compared using Saturn's top-most layer of Ammonia ice, wherein the drag of Bravo was found to have a minimum and maximum values of 17.2 and 114 Newtons respectively, while Alpha had minimum and maximum values of only 0.185 and 1.22 Newtons, over ten times less than Bravo.

Ultimately, the experiments could have yielded a larger range of data and given more comprehensive results if a better a better mounting system had been used to attach the model to the force gauge. Despite the decrease in data range design Bravo followed the expected trend for a flat plate perpendicular to the flow, that being a flat drag coefficient as the Reynolds number increases with a slight increase in the lower Reynolds numbers. Unfortunately, the drag coefficient was higher than expected for design Alpha, this error is likely due to either misalignment in the test section or some observed surface defects that may have caused more skin friction drag than a truly streamlined design would have.

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Appendix

Tables

Table A1: Coefficient of Drag and Reynolds number for Design Alpha

Reynolds Number	Coefficient of Drag	Q (inH2O)	Uncorrected Drag (kg)
18589.044	8.196	0.015	0.0035
47996.706	1.229	0.100	0.0035
76041.083	0.980	0.251	0.0040
107216.519	0.739	0.499	0.0045
131707.019	0.653	0.753	0.0050
151703.002	0.861	0.999	0.0065
169897.491	0.785	1.253	0.0070
186014.328	0.737	1.502	0.0075
200899.327	0.702	1.752	0.0080
214701.449	0.737	2.001	0.0090
227516.536	0.766	2.247	0.0100
239791.465	0.739	2.496	0.0105
251925.560	0.759	2.755	0.0115
262801.140	0.738	2.998	0.0120
272906.754	0.723	3.233	0.0125
283261.903	0.741	3.483	0.0135
293683.367	0.755	3.744	0.0145
303633.701	0.737	4.002	0.0150

Table A2: Coefficient of Drag and Reynolds number for Design Bravo

Reynolds Number	Coefficient of Drag	Q (inH2O)	Uncorrected Drag (kg)
7119.062	5.644	0.002	0.0055
34610.917	0.819	0.052	0.0140
41288.327	0.935	0.074	0.0215
47996.706	0.958	0.100	0.0290
50339.370	0.951	0.110	0.0315
52796.376	0.938	0.121	0.0340
55144.017	0.941	0.132	0.0370
56790.468	0.950	0.140	0.0395
58979.340	0.951	0.151	0.0425
60900.992	0.958	0.161	0.0455
62580.048	0.960	0.170	0.0480
64572.964	0.941	0.181	0.0500
66158.893	0.934	0.190	0.0520
67877.592	0.976	0.200	0.0570
70048.886	0.983	0.213	0.0610
71352.233	0.963	0.221	0.0620
73106.404	0.979	0.232	0.0660
74356.177	0.976	0.240	0.0680
75432.744	0.977	0.247	0.0700
77392.363	0.996	0.260	0.0750
79303.573	0.975	0.273	0.0770
80457.140	0.978	0.281	0.0795
82016.807	0.972	0.292	0.0820
83822.643	0.989	0.305	0.0870
84914.841	0.986	0.313	0.0890
86127.009	0.980	0.322	0.0910
87585.769	0.980	0.333	0.0940
88761.470	0.985	0.342	0.0970
89407.956	0.992	0.347	0.0990
91067.346	0.985	0.360	0.1020
92572.694	0.992	0.372	0.1060

93685.832	0.996	0.381	0.1090
94907.342	0.989	0.391	0.1110

Table A3: Comparable Reynolds Numbers for Earth (See Ref. 4)

Altitude (km)	Density (kg/m^3)	Viscosity (Ns/m^2)	Velocity (m/s)	Reynolds Number
80000	1.85E-05	1.32E-05	13.167	6
70000	8.28E-05	1.44E-05	13.167	26
60000	3.10E-04	1.58E-05	13.167	89
50000	1.03E-03	1.70E-05	13.167	273
40000	4.00E-03	1.60E-05	13.167	1,130
30000	1.84E-02	1.48E-05	13.167	5,653
25000	4.01E-02	1.45E-05	13.167	12,537
20000	8.89E-02	1.42E-05	13.167	28,319
15000	0.195	1.42E-05	13.167	62,047
10000	0.414	1.46E-05	13.167	128,455
9000	0.467	1.49E-05	13.167	141,705
8000	0.526	1.53E-05	13.167	155,961
7000	0.590	1.56E-05	13.167	171,192
6000	0.660	1.60E-05	13.167	187,449
5000	0.736	1.63E-05	13.167	204,877
4000	0.819	1.66E-05	13.167	223,440
3000	0.909	1.69E-05	13.167	243,124
2000	1.007	1.73E-05	13.167	264,255
1000	1.112	1.76E-05	13.167	286,497
0	1.225	1.79E-05	13.167	310,142

Table A4: Estimated Atmospheric Properties of Saturn’s Layers (See Refs. 1 and 2)

	Ammonia Ice Layer	Water Ice Layer	Ammonium Hydrosulfide Ice	Water Ice (band)	Water Droplets with Aqueous Ammonia Solution
Temperature (K)	130	185	213	270	300
Pressure (kPa)	125	250	450	950	1500
Gas Constant (J/kg*K)	488.196	461.523	162.675	461.523	474.485
Density (kg/m^3)	1.970	2.928	13.018	7.624	10.538
Viscosity- Low Estimate (Ns/m^2)	2.00E-06	2.00E-06	2.00E-06	2.00E-06	2.00E-06
Viscosity- High Estimate (Ns/m^2)	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05
Velocity (m/s)	13.167	13.167	13.167	13.167	13.167
Reynolds Number- High Estimate	4,460,433	6,631,008	29,480,728	17,265,180	23,864,492
Reynolds Number- Low Estimate	297,362	442,067	1,965,382	1,151,012	1,590,966

Figures

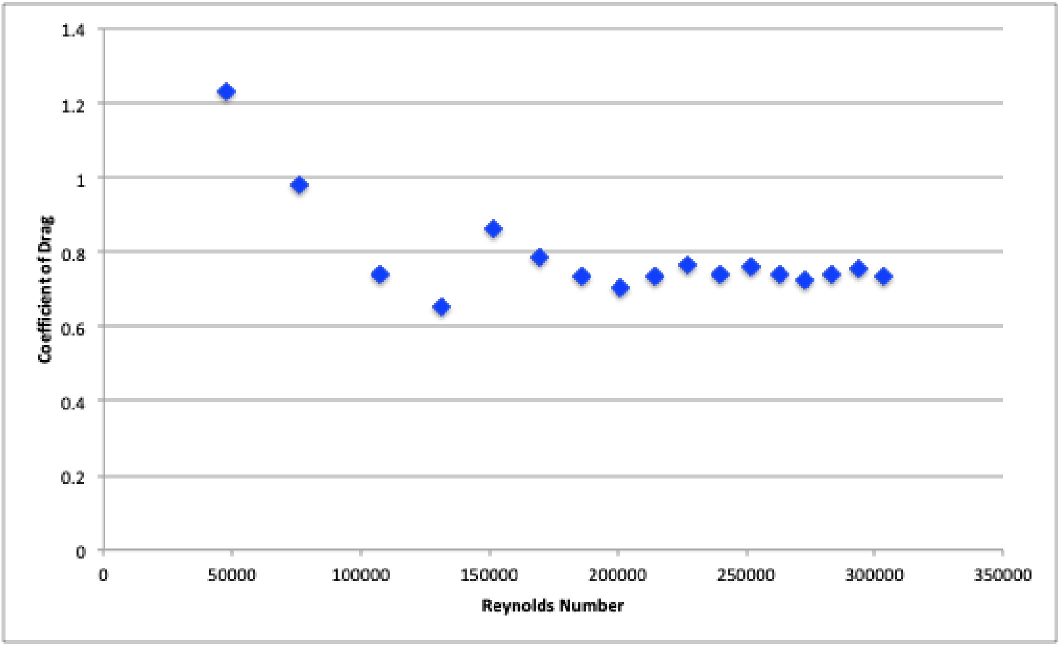

Figure A1: Reynolds Number vs Coefficient of Drag for Design Alpha

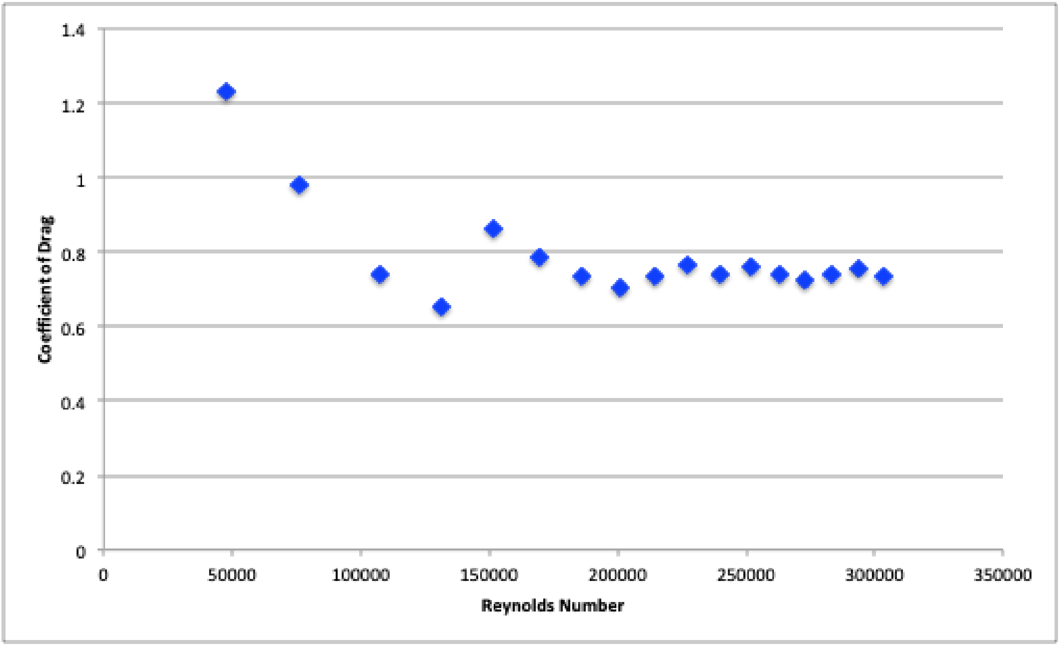

Figure A2: Reynolds Number vs Coefficient of Drag for Design Bravo

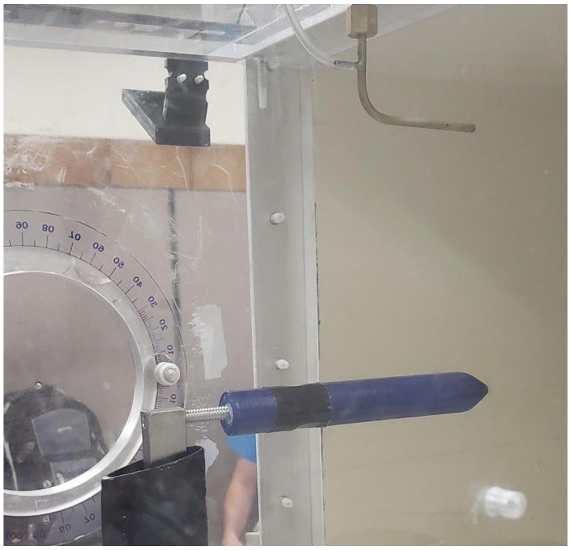

Figure A3: Sonde Alpha in the Wind Tunnel

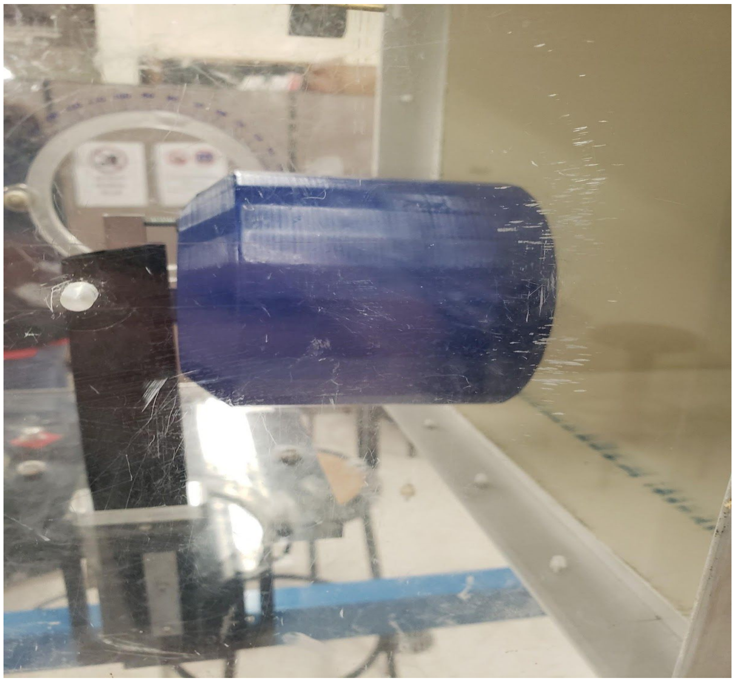

Figure A4: Sonde Bravo in the Wind Tunnel

Equations

$$D = D_{meas} - D_{tare} \tag{1}$$

$$q = \frac{1}{2}\rho v^2 \tag{2}$$

$$Re = \frac{\rho v l}{\mu} \tag{3}$$

$$\mu = \frac{1.458*10^{-6}\sqrt{T}}{1+\frac{110.4}{T}} \tag{4}$$

$$P = \rho R T \tag{5}$$

$$C_D = \frac{D}{\frac{1}{2}\rho v^2 A} \tag{6}$$

Sample Calculations

$$D = (0.0065 - .003) * 9.81 = 0.0343\ N \tag{1}$$

$$248.84 = \frac{1}{2} * 1.171 * v^2 \therefore v = 20.616\ m/s \tag{2}$$

$$Re = \frac{1.171*20.616*0.1143}{1.818*10^{-5}} = 151780 \tag{3}$$

$$\mu = \frac{1.458*10^{-6}\sqrt{294.15}}{1+\frac{110.4}{294.15}} = 1.818 * 10^{-5}\ Pa*s \tag{4}$$

$$98900 = \rho * 287 * 297.15 \therefore \rho = 1.171\ kg/m^3 \tag{5}$$

$$C_D = \frac{0.0343}{\frac{1}{2}*1.171*20.616^2*1.603*10^{-4}} = 0.8599 \tag{6}$$