



Yannis Apostolakopoulos

Design of a Fixed Wing Martian Aerial Vehicle and Low Reynolds
Number Airfoil Analysis

Engineering
MSc in Astronautics and Space Engineering

MSc
Academic Year: 2024 - 2025

Supervisor: Vaios Lappas
September 2025



Engineering
Astronautics and Space Engineering
MSc

Academic Year 2024 - 2025

Yannis Apostolakopoulos

Design of a Fixed Wing Martian Aerial Vehicle and Low Reynolds
Number Airfoil Analysis

Supervisor: Vaios Lappas
September 2025

This thesis is submitted in partial fulfilment of the requirements for
the degree of MSc in Astronautics and Space Engineering

© Cranfield University 2025. All rights reserved. No part of this
publication may be reproduced without the written permission of the
copyright owner.

Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

Abstract

The objective of this thesis is to evaluate the feasibility of a fixed-wing, VTOL capable aircraft for use in the Martian atmosphere which would address a gap in low Reynolds number research for Martian flight. This project is supposed to take over from the limitation NASA's Ingenuity rotorcraft experienced, promising longer range and higher efficiency. The **Martian Aerial Exploration Validation Experiment (MAEVE)** is a proposed compact 5kg demonstration platform due to operate in the densest part of the Martian atmosphere (Hellas Basin) to bridge the gap between simple rotorcraft and the future of planetary aerial exploration.

This research uses a combination of accurate Martian atmospheric data from the Mars Climate Database v6.1 (Forget, et al., n.d.) and an airfoil analysis tool (xfoil v6.99) to produce a comparative study between several airfoils that have been selected for their use in low-Re research, along with a wing sizing study to determine appropriate wing area and velocities to maintain steady level flight in the Martian Atmosphere.

Results have indicated one of the best suited airfoils for this vehicle is the SD7003 airfoil, selected for its exemplary low Re efficiency and steady/gradual stall behaviour. Traveling at 40m/s using the SD7003 airfoil, the vehicle would require wings of approximately 1.25m in length and 0.4m in chord length. The vehicle would be powered by an electrically driven counter rotating co-axial pair of propellers and will be controlled aerodynamically using control surfaces during flight, and during VTOL manoeuvres it would be controlled by gimbling the propellers.

The study concludes that a 5kg MAEVE concept is technically feasible and capable of producing valuable data for the future generations of planetary aerial exploration.

Keywords:

Airfoil, Air Density, Mars, fixed wing, Validation, Viscosity

Table of Contents

Academic integrity declaration.....	i
Abstract.....	ii
List of Figures.....	v
List of Tables.....	vii
List of Equations.....	viii
List of Abbreviations.....	ix
1 Introduction.....	1
2 Literature Review	3
2.1 Planetary Aerial Vehicle Concepts.....	3
2.2 Case Study: NASA's Mars Ingenuity Rotorcraft.....	4
2.3 Prior work on airfoils for low density atmospheres.....	6
2.4 Synthesis and Gaps in the Literature.....	7
3 Martian Atmospheric Conditions.....	8
3.1 Air Density and Viscosity	9
3.2 Unique Challenges.....	12
3.2.1 Dust storms	12
3.2.2 Solar Irradiance.....	14
3.2.3 Winds	15
3.3 Summary of Martian conditions	16
4 Methodology.....	18
4.1 Equations and Assumptions	18
4.2 Validation of Scripts	19
4.2.1 Comparison of S1223 airfoil in Earth's Atmosphere.....	20
4.2.2 Calculating wing surface area	23
5 Martian Aerial Exploration Validation Experiment (MAEVE) Design	
Concept.....	24
5.1 System Overview and Requirements.....	25
5.2 Flight Plan for Hellas Basin.....	27
5.3 Subsystems	28
5.3.1 Electrical Energy	28
5.3.2 Propulsion and Lift	28
5.3.3 Optics and Payload	29
5.3.4 Survivability	29
5.3.5 Flight Controls	30
5.4 Summary of Vehicle Design.....	30
6 Airfoil Tradeoffs	32
6.1 Airfoil Requirements.....	33
6.2 Shortlist.....	34
6.3 Simulation Conditions	35

6.4 Performance of Shortlisted Designs in Martian Atmosphere.....	36
6.4.1 Lift to Drag Ratio (CL/CD vs AoA) at Low Speed	37
6.4.2 Stall Behaviour (CL vs AoA) at Low Speeds	40
6.4.3 Further Analysis: Lift to Drag Ratio (CL/CD vs AoA) at High Speed.....	43
6.4.4 Further Analysis: Stall Behaviour (CL vs AoA) at High Speeds.....	46
6.5 Airfoil Selection Summary	49
7 Wing Design	50
7.1 Selected Airfoil	50
7.1.1 Properties and Characteristics	50
7.1.2 Materials.....	51
7.1.3 Performance in Martian Atmosphere.....	51
7.2 Deployment Mechanism	53
7.3 Velocity and Wing Area Variations.....	54
7.4 Wing Design Summary	56
8 Results and Discussion	58
8.1 Interpretation of Airfoil Analysis Results.....	58
8.2 Feasibility of Design.....	59
8.2.1 Small 5-10kg Concept.....	59
8.2.2 Larger Future Design Concept.....	60
8.3 Future Work	60
9 Conclusion.....	62
10 References	63
Appendices.....	66
Appendix A Ethical approval letter	66
Appendix B MATLAB Scripts	67

List of Figures

Figure 1: Ingenuity rotorcraft infographic depicting milestones (NASA)	5
Figure 2: The topography of Mars using the Mars Orbiter Laser Altimeter (MOLA) with major regions labelled (Lakdawalla)	8
Figure 3: Air density map of Mars 100m above the surface (Forget, et al., n.d.)	11
Figure 4: Elevation map of Mars relative to its geoid (Forget, et al., n.d.)	11
Figure 5: Air viscosity map of Mars 100m above the surface (Forget, et al., n.d.)	12
Figure 6: Monthly mean visible optical depth (τ) depicting frequency/severity of storms (Forget, et al., n.d.)	13
Figure 7: Mean solar zenith angle in degrees throughout a Martian day by latitude	15
Figure 8: Horizontal wind speeds in m/s (Forget, et al., n.d.)	15
Figure 9: Cl/Cd polar for S1223 computed by xfoil and varying fixed Reynolds values (Lakdawala & Shaikh, 2018)	20
Figure 10: Cl/Cd polar for S1223 computed by xfoil using custom MATLAB script Airfoil_Analysis_Validation_Copy.m	21
Figure 11: xfoil plot for Re=100 000 at Alpha=9 (Not Converged)	22
Figure 12: Xfoil plot for Re=100 000 at Alpha=9 (Converged)	23
Figure 13: MAEVE preliminary design, annotaed diagram of vehicle landed on Martian surface (Not to Scale).	24
Figure 14: MAEVE preliminary design, force diagram of steady and level flight at constant speed (Not to Scale).	25
Figure 15: MAEVE preliminary design, annotated top-down view diagram of vehicle in flight with approximate dimensions (Not to Scale).	31
Figure 16: Flowchart representing airfoil selection and wing design process ...	32
Figure 17: CL/CD against AoA in Hellas Basin at Velocity = 20m/s	38
Figure 18: CL/CD against AoA in Hellas Basin at Velocity = 30m/s	38
Figure 19: CL/CD against AoA in Southern Highlands at Velocity = 20m/s	39
Figure 20: CL/CD against AoA in Southern Highlands at Velocity = 30m/s	39
Figure 21: CL against AoA in Hellas basin at Velocity = 20m/s	41
Figure 22: CL against AoA in Hellas basin at Velocity = 30m/s	41

Figure 23: CL against AoA in Southern Highlands at Velocity = 20m/s	42
Figure 24: CL against AoA in Southern Highlands at Velocity = 30m/s	42
Figure 25: CL/CD against AoA in Hellas basin at Velocity = 40m/s	44
Figure 26: CL/CD against AoA in Hellas basin at Velocity = 50m/s	44
Figure 28: CL/CD against AoA in Southern Highlands at Velocity = 50m/s	45
Figure 27: CL/CD against AoA in Southern Highlands at Velocity = 40m/s	45
Figure 29: CL against AoA in Hellas basin at Velocity = 40m/s	47
Figure 30: CL against AoA in Hellas basin at Velocity = 50m/s	47
Figure 31: CL against AoA in Southern Highlands at Velocity = 40m/s	48
Figure 32: CL against AoA in Southern Highlands at Velocity = 50m/s	48
Figure 33: SD7003 airfoil geometry (AirFoil Tools, n.d.)	50
Figure 34: CL vs AoA of the SD7003 airfoil at regular Reynold number intervals (20k-70k)	52
Figure 35: L/D ratio vs AoA of the SD7003 airfoil at regular Reynold number intervals (20k-70k)	52
Figure 36: Wing surface area required for a 5Kg vehicle, to maintain level flight in Hellas Basin at varying velocities of cruise	55
Figure 37: Wing surface area required for a 10Kg vehicle, to maintain level flight in Hellas Basin at varying velocities of cruise	56

List of Tables

Table 1: Summary of atmospheric and sunlight variables per notable region. Green shows desirable values whilst red shows least desirable for each variable. All data taken from relevant figures in chapter 3 above	17
Table 2: List of MATLAB scripts used	19
Table 3: Table of preliminary requirements for the MAEVE.	26
Table 4: Copy of the Airfoil Requirements from the complete table of requirements (Table 3).	33
Table 5: Airfoils shortlisted for their beneficial characteristics, initially discussed in chapter 2.3: Prior work on airfoils for low density atmospheres.	34
Table 6: Calculated Reynolds number for low-speed flight at each of the 5 predesignated regions using Equation 1.....	35
Table 7: Calculated Reynolds number for high-speed flight at each of the 5 predesignated regions using Equation 1.....	36
Table 8: Analysis of wing length requirements at regular intervals of velocity for a 5kg vehicle with 2 wings of chord length 0.4m.....	57

List of Equations

Equation 1: Reynolds Number..... 18

Equation 2: Lift 18

Equation 3: Drag 18

List of Abbreviations

AoA	Angle of Attack (Alpha)
CD	Coefficient of Drag
CL	Coefficient of Lift
IT	Information Technology
MAEVE	Martian Aerial Exploration Validation Experiment
Re	Reynolds number
VTOL	Vertical Take Off / Landing

1 Introduction

Mars is one of our closest celestial neighbors, and one that has intrigued humans with its red tint throughout history. With every advancement in space exploration technology, curiosity about Mars continues to increase as new discoveries are made from geological features carved out by ancient running water, to its global dust storms that occur regularly in an atmosphere 1/100 the density of Earth's.

One of the largest bottle necks in Martian exploration is the ground speed of vehicles, crawling across the surface covering minor distances each Martian day (each Sol). Part of the reason Martian rovers travel so slowly is simply a safety measure as the terrain is very unpredictable, covered in sand, rock and loose sharp rocks that can cause permanent damage to a wheel, like in the case of the curiosity rover's aluminum wheels. Being so far from Earth, the rovers must be able to make their own navigational decisions around these obstacles to avoid the one-way communications delay of up to ~20 minutes, and this is where aerial exploration comes in.

Aerial exploration avoids the issue of ground obstacles for the vehicle itself, allowing for autonomous landing location decisions as it descends towards the surface. Additionally, an aerial vehicle could work in tandem with a rover to provide real time high-definition visuals of the surrounding area to not only help the rover navigate dangerous terrain, but also to locate spots of scientific interest for the rover to navigate towards.

Martian flight, however, is not easy to achieve. The Martian atmosphere as previously mentioned is extremely thin and prone to dust storms, bringing numerous challenges discussed throughout the paper. Additionally, Mars is slightly further from the sun than Earth, reducing the amount of sunlight available for solar charging, one of the only viable forms of energy production on the surface, certainly the most lightweight.

This paper aims at creating a design for a Martian Aerial Exploration Validation Experiment (MAEVE), a small vehicle with a targeted mass of 5kg designed to fly

at high speeds and perform Vertical Take-Off and Landing (VTOL) maneuvers in areas of particular interest. The vehicle's primary goal is to validate the use of fixed wings in a Martian atmosphere, with the focus of this paper being on the airfoil comparison and selection for the very low Reynolds number environment the Martian atmosphere provides.

The work conducted in this paper is structured as follows: chapter 2 below will initially be an overview and literature review of existing and proposed planetary aerial exploration designs and low Re airfoils, followed by an analysis of the Martian atmospheric conditions in various regions of interest in chapter 3. Chapter 4 provides a methodology for the creation of all the airfoil analysis plots analyzed afterwards. This is then followed by chapter 5 which provides a systems overview of the proposed vehicle, with requirements and design decisions. Chapter 6 analyses various airfoils to determine which airfoil exhibits the best desired properties to function optimally in the Martian atmosphere. Chapter 7 then expands upon the airfoil selection by selecting one that provides promising results and performing further analysis under varying conditions, predicting the required velocities and wing areas for steady level flight of a 5kg vehicle. Chapters 8 discuss the results and feasibility of the proposed MAEVE design and discusses the feasibility of a larger future design for powered fixed-winged flight on Mars. Finally, chapter 9 brings a conclusion to the paper summarizing the results.

2 Literature Review

Extraterrestrial exploration has evolved greatly over the years since the first artificial satellite to orbit earth in 1957, Sputnik 1, with a drive to explore other planets fueling the development of space technologies. These advancements have resulted in tens of thousands of concept vehicles adapted to various planetary conditions, few of which have ever made it past the concept phase.

2.1 Planetary Aerial Vehicle Concepts

There are 4 concept families that have been formed for planetary aerial exploration, each bringing unique advantages and disadvantages: balloons, rotorcrafts, fixed-wing aircrafts and gliders. Only 2 of the designs have been proven in extraterrestrial atmospheres, being the balloons and rotorcraft, neither of which were designs with wings and served primary functions of validating technology, with scientific data collection being the secondary mission requirement.

Balloons refer to lighter than air vehicles, which can include architectures like the zero-pressure, super-pressure and Montgolfière. In 1985, what is widely considered as the first atmospheric flight on another planet was conducted on Venus, a planet notorious for its dense hot atmosphere that has destroyed numerous probes within hours of their arrival. These flights consisted of 2 lighter than air balloons deployed in the upper atmosphere which maintained an altitude of roughly 54 kilometres for just under 48 hours, collecting a large amount of data ranging from pressure and temperature to light fluctuations and wind speeds (Sagdeev, Linkin, Blamont, & Preston, 1986). For Venus specifically there have been many proposed concepts, including giant airships, both crewed and uncrewed.

Rotorcrafts are heavier than air vehicles capable of vertical flight by generating lift using rotary wings spinning at high speeds. The Mars Ingenuity rotorcraft marks the first and only powered flight on a planet other than Earth to date but is

only one of countless concepts that exist. A large amount of research has been conducted to complement future designs including high tip-speed rotors, autonomy and flight control systems, thermal/power management and very low Re airfoil behaviour. Multiple rotorcraft concepts have made it out of the theoretical stage and are actively in the development pipeline, with the most anticipated mission being the Dragonfly nuclear powered hex-copter; designed by NASA, APL and dozens of key partners, this rotorcraft is due to operate in Titan's low gravity and thick atmosphere, and would represent a major step in rotorcraft technology, especially regarding its use for space based exploration and scientific research (NASA, Dragonfly, n.d.).

Fixed wing and glider designs are similar to each other, both require wings to generate lift which greatly increases the range and efficiency of the vehicle, the difference lies in that fixed wing designs require a form of propulsion, which often brings lots of complexity and mass, whereas gliders are propulsion less designs, thus having very short lifespans. Gliders are usually designed as extremely simple, low mass and easily storable in order to be deployed either from orbit or from the descent module of a lander. They are ideal for pre landing reconnaissance or a testbed for various technologies including deployment and controlled flight (Pekar, 2015).

2.2 Case Study: NASA's Mars Ingenuity Rotorcraft

Ingenuity was a counter-rotating bi-propeller solar powered rotorcraft with the intention of being a technology demonstration for powered control flight in the Martian atmosphere, launched alongside the Mars perseverance rover in 2020. It was intended to complete up to 5 90-second flights to validate take-off and landing, hovering, short traverses, and vehicle autonomy. In the < 3 years of operation, Ingenuity managed 72 successful flights, each further validating systems and procedures, as well as providing scouting data for the perseverance rover. The vehicle was finally grounded in January 2024 after a rotary wing tip got damaged, serving the rest of its lifespan as a stationary surface outpost

(NASA, NASA's Ingenuity Mars Helicopter Succeeds in Historic First Flight, 2021).



Figure 1: Ingenuity rotorcraft infographic depicting milestones (NASA)

Ingenuity's design faced numerous challenges in order to adapt to flight in the Martian atmosphere which is only ~1% of the air density at sea level on Earth. Generating lift in such a thin atmosphere requires an extremely low mass and high lift coefficient, hence why ingenuity had a mass of only 1.8kg, the rotor blades had to be disproportionally large compared to the body, they had a very high RPM and used a specialized very-low-Reynolds rotor blade airfoil. In most rotorcrafts, the rotating blades generate a torque on the vehicle that needs to be cancelled out, usually using a smaller vertically mounted set of rotating blades like a helicopter tail, but to save mass and complexity, ingenuity used a pair of co-axial counter-rotating propellers which cancel out the induced torque on the body.

Over the 72 flights, Ingenuity covered a total distance of ~17km in just under 130 minutes of flight time, setting altitude and groundspeed records of ~24m and ~10m/s respectively (NASA, NASA's Ingenuity Mars Helicopter Succeeds in Historic First Flight, 2021).

During its lifespan, ingenuity achieved and exceeded multiple milestones and verified the feasibility of powered flight on Mars, some of the key takeaways from the mission included:

- Energy and solar panel management on a lightweight vehicle.
- Reliability and autonomy in thin atmospheres.
- Flight control challenges under low density.
- Scientific and practical importance of aerial exploration.

2.3 Prior work on airfoils for low density atmospheres

In Mars-like atmospheric conditions, airfoils tend to be dominated by transitional boundary layers and laminar separation bubbles. These have significant effect on the stall behaviour and general efficiency (CL/CD) of the airfoil meaning that in depth analysis is required. Additionally, the CO₂ rich atmosphere on Mars can have unaccounted for effects on the aerodynamic behaviour of the airfoil, thus requiring further analysis with specialised CFD software and air composition/density adjustable wind tunnels (Aprovitola, Iuspa, Pezzella, & Viviani, 2024). A good start is to determine a series of earth condition proven airfoils that function well in low Reynolds environments.

S1223 is an airfoil that has been widely studied and used as a starting reference for micro-UAVs and low-speed application. Often used as a validation airfoil, it provides high lift and efficiency at low Re and predictable behaviour, especially in the range of 50,000 – 200,000 Re. This paper uses the S1223 airfoil to validate the MATLAB scripts and XFOIL commands and results, explored in **chapter 4.2: Validation of Scripts**.

Eppler 387 and **SD7003** are both also well studied and documented airfoils often used in low Re research papers, with SD7003 being notorious for minimising adverse separation bubble effects in those conditions (Aprovitola, Iuspa, Pezzella, & Viviani, 2024).

Whilst NACA profile wings are generally not considered to be very well suited to low Re conditions, **NACA 4412** and **NACA 6412** exhibit decent behaviour at low Re conditions, and can often serve as a baseline to put other low Re airfoils into perspective (Vuong, Nguyen, & Le, 2025). The first value in the naming convention for NACA profile airfoils represents the camber percentage, thus having the 2 airfoils in the comparative study later in this paper serves as a method of associating the effect of an increased camber on an otherwise identical airfoil under low Re conditions.

A growing number of research papers revisit the use of **thin cambered plates** for light vehicles and micro-UAVs due to their simple design and manufacturability as well as general effectiveness in low Re conditions (Vuong, Nguyen, & Le, 2025). Thus, this paper analyses 3 separate cambered plates of varying geometries alongside the aforementioned airfoils, in order to determine their effectiveness in comparison to purposefully designed low Re airfoils.

2.4 Synthesis and Gaps in the Literature

This paper focuses on addressing the major drawback of using a helicopter style design for aerial exploration: efficiency and range. As aforementioned, Ingenuity covered 17km over all its flights during a 3-year period, a fix winged adaptation could have the potential to cover the same horizontal distances within a single flight. This would unlock the ability to scout out large swaths of land and to rapidly relocate the scientific equipment on board to locations of interest rather than being confined to the proximity of the landing location.

One of the largest gaps in research for Martian aerial exploration is the lack of experimental data for the use of wings in the atmosphere. Many designs have been proposed from gliders to balloons, however, none have made it to final design phases. MAEVE is a project devised to generate this data in order to validate the feasibility of a fixed wing design and provide flight test data to help improve airfoil and wing simulation software for very low Re, as well as aiding in the development of future concepts.

3 Martian Atmospheric Conditions

Mars is one of the most well studied planets in the solar system thanks to the numerous active and past missions to the red planet, more than half of which have unfortunately resulted in failures. Failed attempts aside, there are currently more robotic instruments/vehicles on Mars than any other extraterrestrial body, spread across the various regions of mars with the similar goals of studying our closest neighbouring planet (The Planetary Society, n.d.). As with any planet with an atmosphere, Mars experiences seasons, weather patterns, variations in atmospheric conditions and much more, which need to be understood for a mission to the surface to have a chance of being successful.

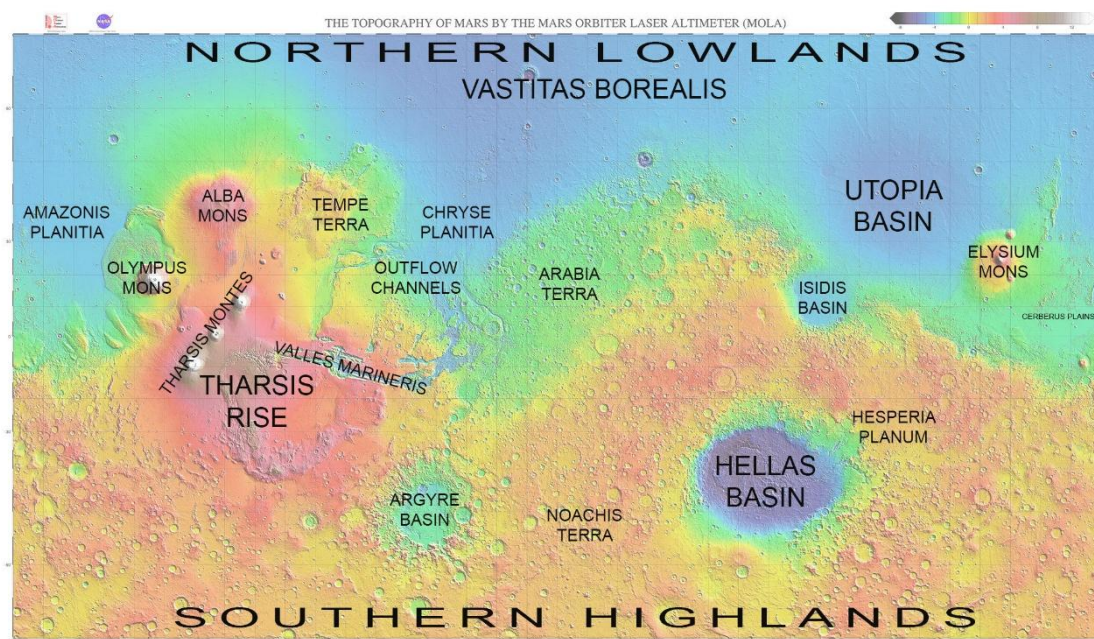


Figure 2: The topography of Mars using the Mars Orbiter Laser Altimeter (MOLA) with major regions labelled (Lakdawalla)

3.1 Air Density and Viscosity

Using the Mars Climate Database v6.1 (Forget, et al., n.d.), maps of Mars can be generated to depict necessary variables using real data from past missions. Since a large portion of this paper focuses on determining an appropriate airfoil it is important to properly understand the atmospheric conditions near the surface. In **Equation 1: Reynolds Number**, it can be seen that the Reynolds number is directly proportional to the air density and relative velocity, whereas it is inversely proportional to the air viscosity. With such a thin atmosphere, any increase in Reynold number could have a significant effect on the efficiency of the airfoil/wing, therefore, it would be beneficial for the design of the vehicle if it were to operate in an area that maximises the air density and minimises the viscosity.

In **Figure 3**, the air density map of Mars, there are a few regions that stand out, most notably:

Tharsis Rise	The large highland area from roughly $150^{\circ}W$ $15^{\circ}N$ to $60^{\circ}W$ $45^{\circ}S$, where air density varies around 0.009 kg/m^3 ($9.0\text{e-}03$).
Argyre Basin	The large crater centred around $40^{\circ}W$ $50^{\circ}S$ where air density is notably higher than the surrounding regions, averaging at approximately 0.025 kg/m^3 ($2.5\text{e-}02$).
Hellas Basin	The larger and deeper crater centred around $70^{\circ}E$ $40^{\circ}S$, where air density is at the highest across the planet's surface, reaching an average of approximately 0.032 kg/m^3 ($3.2\text{e-}02$). This Crater has an approximate diameter of 2,300km.

All of these regions have their respective notable air densities due to relative elevation differences between them, see **Figure 4** to visualise the elevation variance about the Mars geoid.

In **Figure 5**, the air viscosity map of Mars, there are also a few regions that stand out:

Chryse Planitia A large area encompassing lowlands and mountainous regions, located between roughly $60^{\circ}W$ $60^{\circ}N$ to $15^{\circ}W$ $0^{\circ}N$, where air viscosity varies around $1.2e-05$ Ns/m².
(and surrounding regions)

Southern Highlands Areas at a lower latitude than $45^{\circ}S$ experience the lowest average temperatures on the planet, thus also having the lowest average viscosity at approximately $8.0e-06$ Ns/m².

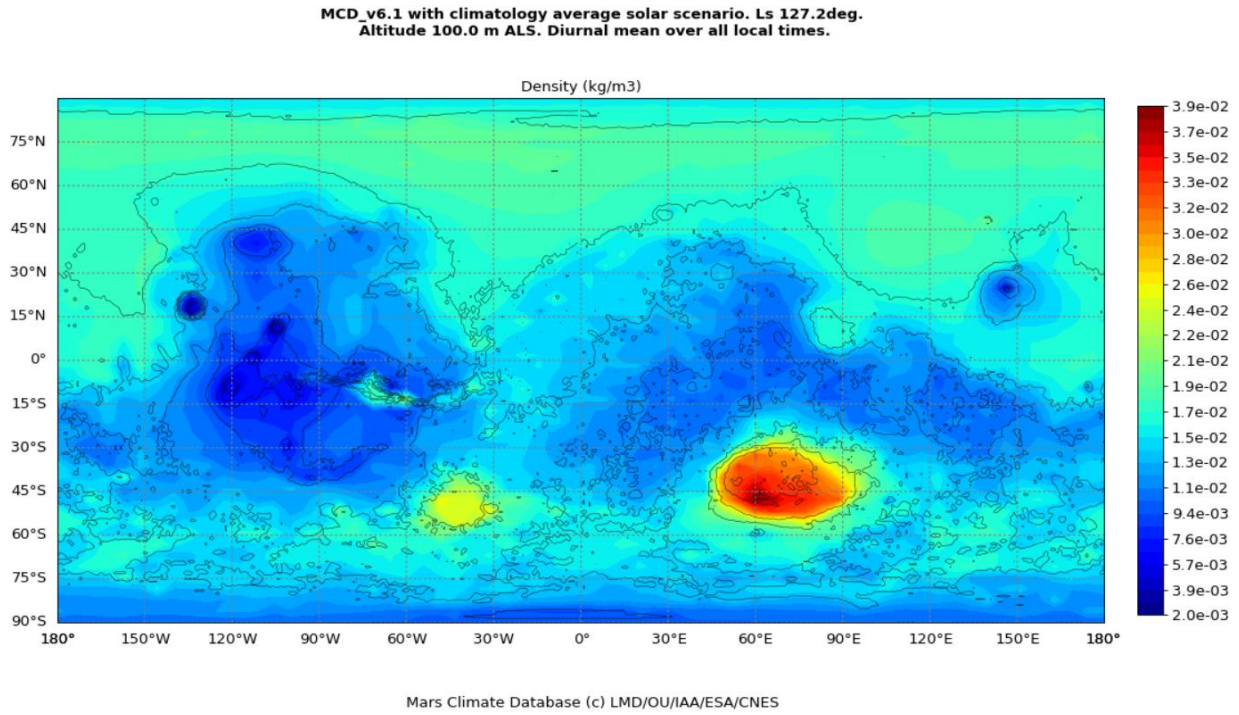


Figure 3: Air density map of Mars 100m above the surface (Forget, et al., n.d.)

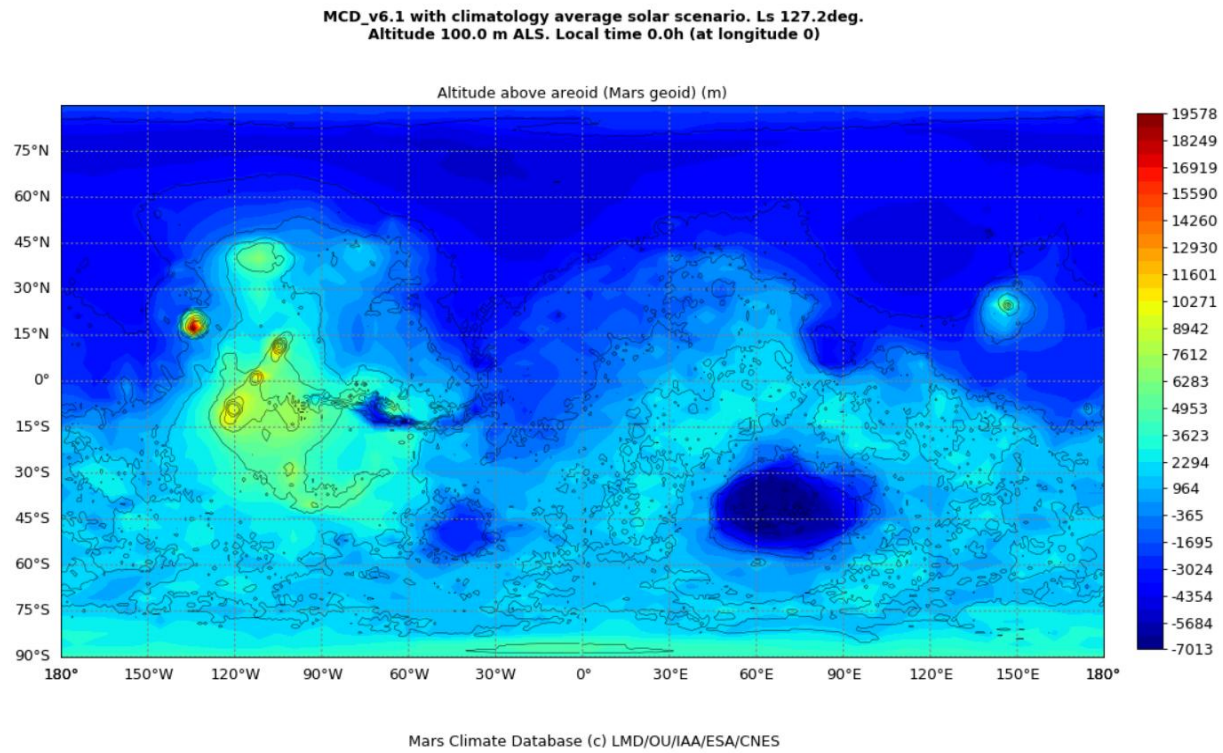


Figure 4: Elevation map of Mars relative to its geoid (Forget, et al., n.d.)

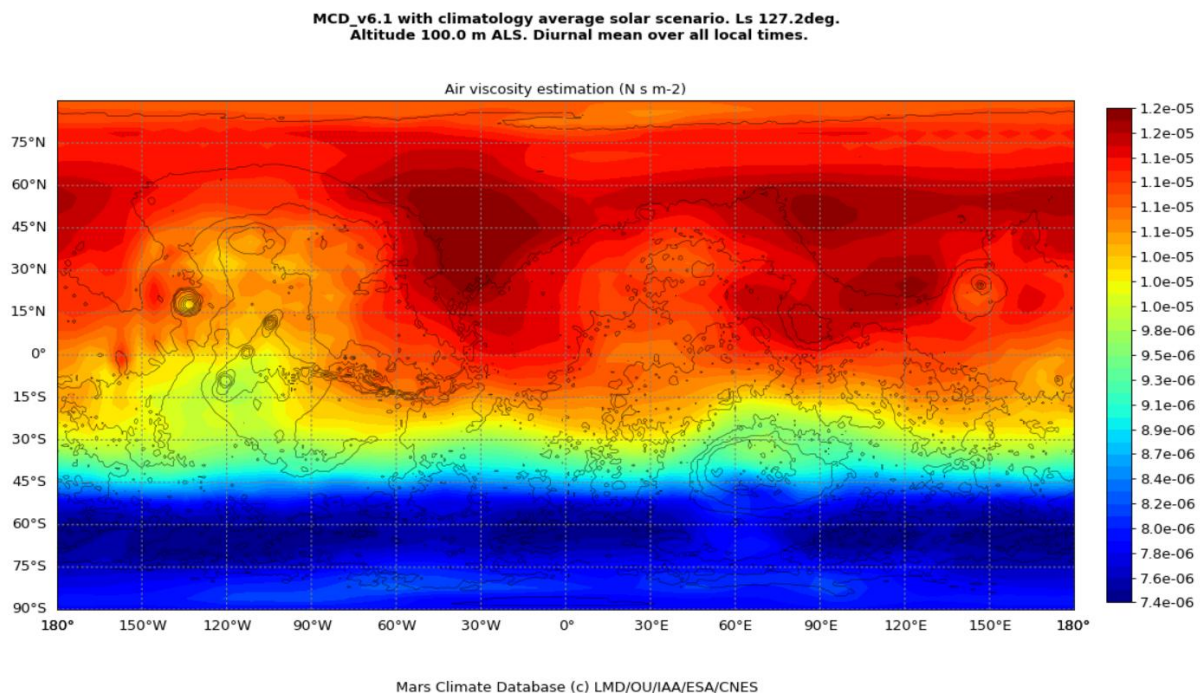


Figure 5: Air viscosity map of Mars 100m above the surface (Forget, et al., n.d.)

3.2 Unique Challenges

From having a very thin atmosphere comprised mostly of CO₂, to global scale dust storms that can block out sunlight for a few dozen days per year, the Martian landscape is not exactly a hospitable environment.

3.2.1 Dust storms

Mars' dust storms can be categorized as either a local storm, or a global storm often engulfing the majority of the planet. These global storms usually occur up to 2 times per year and can last up to 70 Martian days, but more often than not they occur a single time per year around Mars' perihelion, the lowest point in the eccentric orbit around the sun (Appelbaum & Flood, 1989).

On the other hand, local dust storms occur regularly throughout the Martian year and can occur anywhere on the surface, however, it was found that they tend to occur more often around latitudes of 10° to 20° N and 20° to 40° S. These smaller

storms typically only last a few days and cause minor disruptions to surface activity, with a worst case being a stop in activity for 48-72 hours (Appelbaum & Flood, 1989).

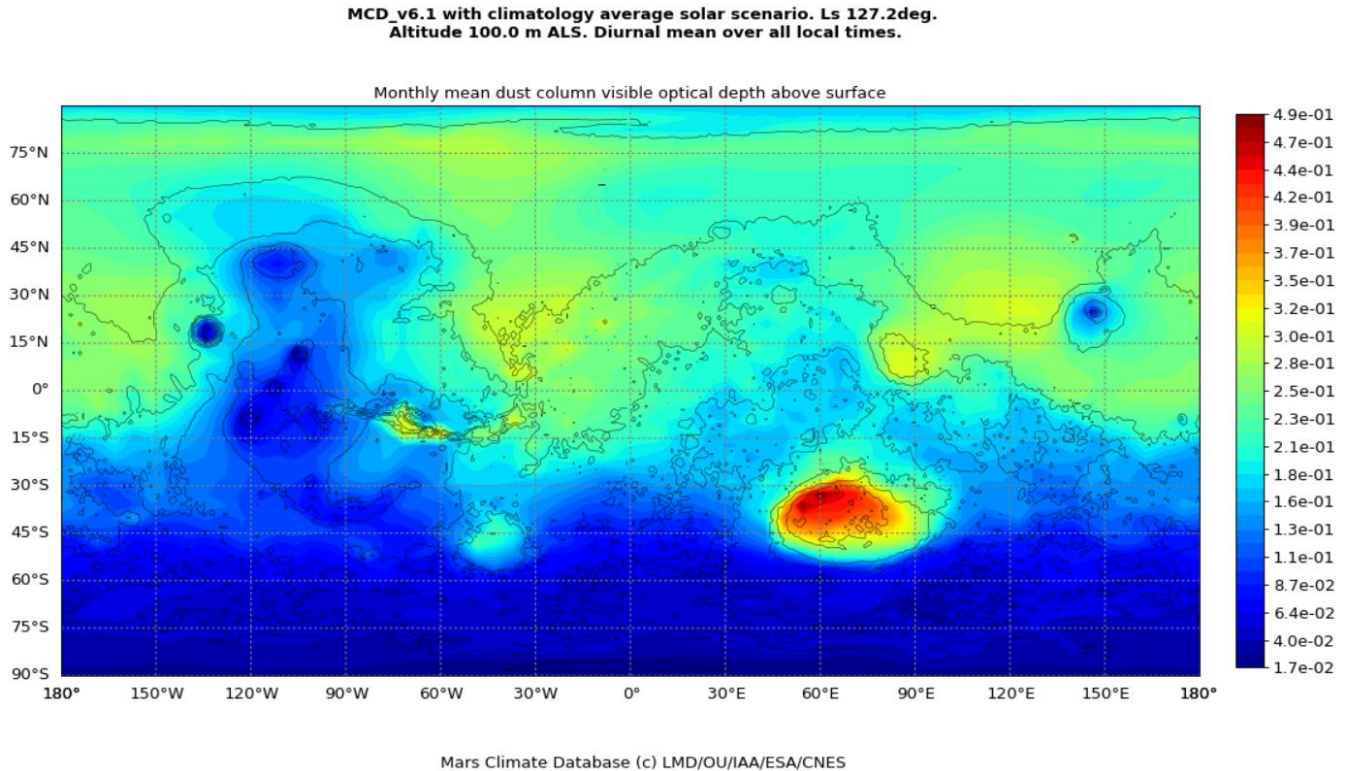


Figure 6: Monthly mean visible optical depth (τ) depicting frequency/severity of storms (Forget, et al., n.d.)

In **Figure 6** the visible optical depth (τ) of each region can be seen on a scale of 0.017 in the southern highlands and mountain peaks, to just under 0.5 in the Hellas basin at 30°S 60°E. A τ value of 0.5 equates to approximately 40% of the visible light being blocked or absorbed before reaching the surface. This makes sense for Hellas basin as it can act as a sort of hotspot for dust build up, with many of the global scale dust storms either originating from Hellas basin, or nearby regions (Chow & Chan).

3.2.2 Solar Irradiance

The solar irradiance on the Martian surface mainly relies on 3 factors: The distance between the planet and the sun, the opacity of the atmosphere and the zenith angle of the sun.

Mars is our closest neighbouring planet, and the 4th from the sun in the solar system, therefore most missions have historically relied on solar power. With the perihelion of Mars' orbit at only 206.65 million km and the aphelion at 249.2 million km, the average distance from the sun is only ~1.5x that of Earth (Williams, 2025).

The opacity of the atmosphere is greatly dependant on the dust conditions discussed in chapter 3.2.1 above, with regions such as Hellas basin expected to have up to 40% **less** sunlight reach the surface on average. It is also expected that during the global scale dust storms, an almost complete blockage of sunlight occurs which historically is where many missions (such as the opportunity rover) have ended or were planned to live up to; this is due to temperatures plummeting and there rarely being sufficient battery power to keep the vehicle functional and warm throughout the storm, especially after a few years of battery and solar panel degradation (Aprovitola, Iuspa, Pezzella, & Viviani, 2024).

The zenith angle component of the total solar irradiance varies throughout the ~24.7 hours of a Martian day (sol), with peak solar energy at the local noon and reduced solar panel efficiency as the sun is at lower angles in the sky. **Figure 7** below shows the mean zenith angle, and hence how close the sun gets to being directly above the surface. At a latitude of 0°, as expected, the mean zenith angle is 90°. Regions such as the Hellas Basin for example, located in the southern hemisphere, experience a mean zenith angle of approximately 100° to 110°, 10°-20° off being directly above

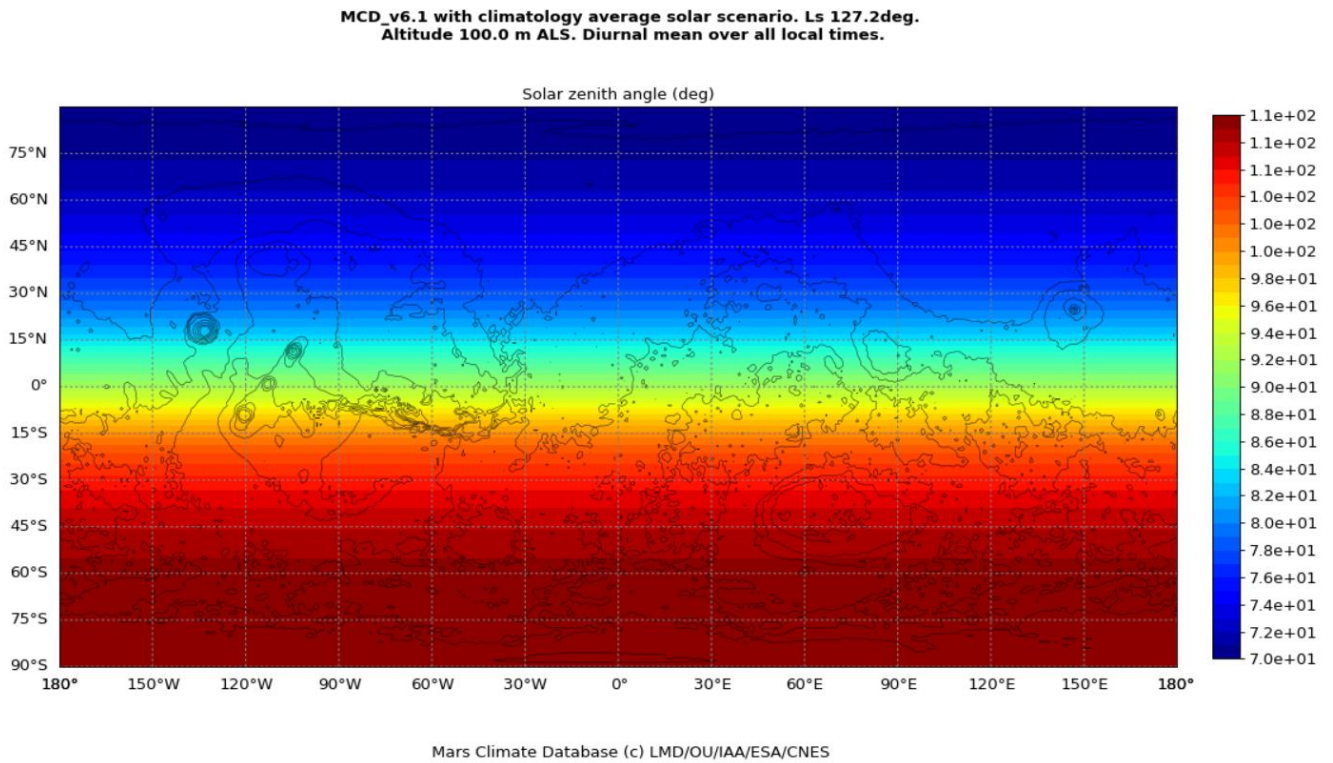


Figure 7: Mean solar zenith angle in degrees throughout a Martian day by latitude (Forget, et al., n.d.)

3.2.3 Winds

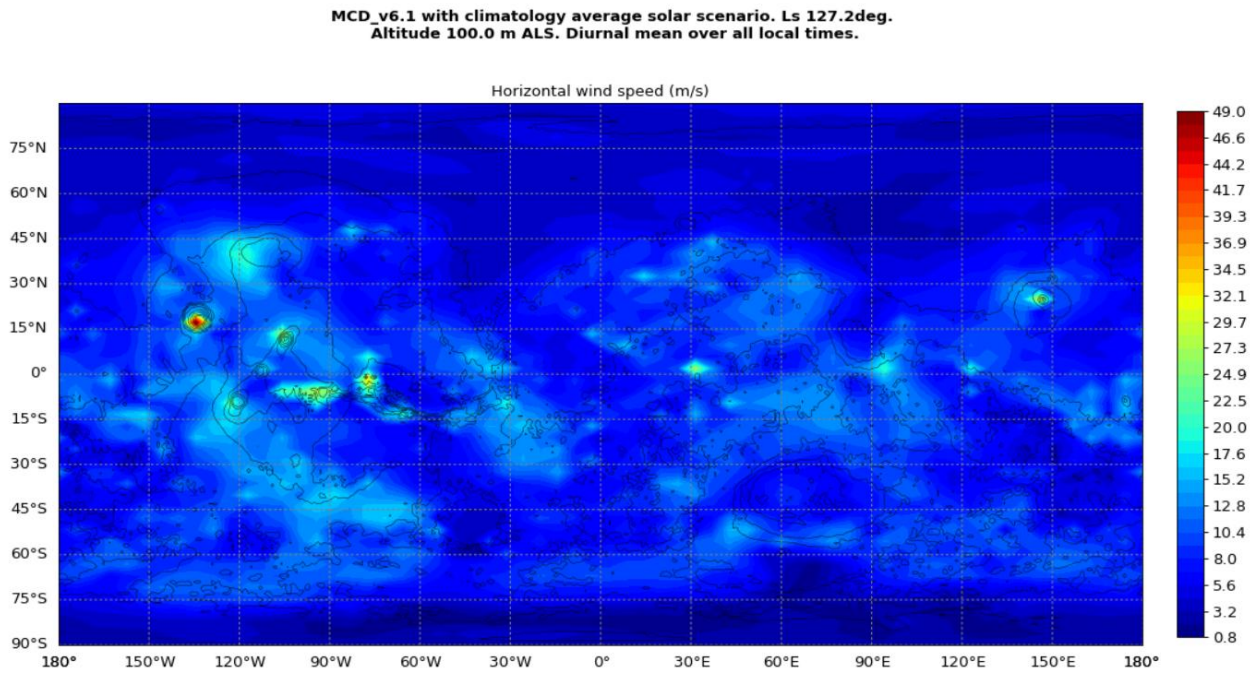


Figure 8: Horizontal wind speeds in m/s (Forget, et al., n.d.)

Since Mars' atmosphere is extremely thin, the wind does not have as large of an impact as on earth, however, for an aerial vehicle it is certainly important to take wind speeds into consideration; most regions experiencing 0-10m/s of horizontal wind velocities, and larger velocities in the highlands as seen in **Figure 8**.

3.3 Summary of Martian conditions

To optimise the performance of an airfoil, a larger air density and smaller air viscosity is preferred. Regions like **Hellas basin** and **Argyre basin** are best suited for this due to their low elevation.

To *optimise solar charging*, optical depth (τ) should be kept to a minimum meaning more sunlight makes it through the Martian atmosphere, this is maximised in **highland regions** where the atmosphere is thinner. For every whole number of τ , the percentage of direct sunlight that makes it through the medium is multiplied by 36.8%, therefore an optical depth of $\tau=1$ means only ~37% of the sunlight makes it through. The Transmittance (percentage of light that makes it through the medium) can be calculated simply as $e^{-\tau}$.

Additionally, the highest angle from the ground the sun will reach at local noon determines the optimum orientation for the solar panel during charging operations, if this value is known it can be accounted for in the design by angling the solar panel no higher than the zenith angle of the sun.

Table 1 below summarises the variables discussed in this chapter by region. The region that has attracted the most intrigue would be **Hellas basin** as it offers the best chance of successful winged flight with significantly larger air density (factor of 3 compared to average), however, also has the largest negative effects caused by storms and dust, thus limiting mission life.

Table 1: Summary of atmospheric and sunlight variables per notable region.
Green shows desirable values whilst red shows least desirable for each variable. All data taken from relevant figures in chapter 3 above

Region Labelled map: Figure 2	Air Density (Kg/m³)	Air Viscosity (Ns/m²)	Optical depth [τ] % of sunlight at surface [e^{-τ]}	Mean Solar zenith (deg)
Tharsis Rise 15°S 110°W	1.00E-02	1.10E-05	0.09 91.3%	100
Chryse Planitia 30°N 30°W	1.70E-02	1.20E-05	0.30 74.1%	75
Southern Highlands < 45°S	1.30E-02	8.00E-06	0.05 95.1%	>110
Argyre Basin 50°S 40°W	2.50E-02	8.10E-06	0.21 81.1%	110
Hellas Basin 40°S 70°E	3.20E-02	9.30E-06	0.44 64.4%	105

4 Methodology

“XFOIL is an interactive program for the design and analysis of subsonic isolated airfoils.” (Drela & Youngren). In this paper it is used to estimate lift and drag coefficients for all the airfoils shortlisted in **chapter 6: Airfoil Tradeoffs**. These coefficients can then be used in the standard lift and drag equations expressed in the following section to generate useful data in different conditions/wing design.

4.1 Equations and Assumptions

$$Re = \frac{\rho * V * c}{\mu}$$

Equation 1: Reynolds Number

The equation to calculate Reynolds number, where ρ is the air density, V is the relative airspeed, c is the chord length and μ is the dynamic viscosity. In MATLAB this equation is written as `(Re = rho*V*c/mu)`.

$$L = C_L \cdot \frac{\rho \cdot V^2 \cdot A}{2}$$

Equation 2: Lift

$$D = C_D \cdot \frac{\rho \cdot V^2 \cdot A}{2}$$

Equation 3: Drag

The equations to calculate the lift and drag forces on the vehicle (**Equation 2** and **Equation 3**), can be used to determine the wing area required or the velocity required for a given area. ρ is the local air density, V is the vehicle velocity relative to the air, for lift, A is the 2D surface area of the lifting body, however for drag it can be approximated as the cross sectional area of the vehicle perpendicular to the direction of travel (O'Connor). Lastly, C_L and C_D are the coefficients of lift and

drag respectively and must be approximated experimentally (e.g. via simulation on xfoil).

4.2 Validation of Scripts

5 MATLAB scripts have been generated with slightly different purposes, but all rely on the same fundamental code hence why only one validation copy is needed. They are summarized below and provided in full in the appendix:

Table 2: List of MATLAB scripts used

Script names	Function	Appendix
Airfoil_Analysis_Validation_Copy.m	Validate the results produced against existing data for the S1223 airfoil at various Reynolds numbers	10B.1
Airfoil_Analysis_Comparisson_Plots.m	Modification from the validation copy that plots CL/CDvAoA for all inputted airfoils at a given Reynolds number	10B.2
Airfoil_Analysis_Comparisson_Plots_CL_Stall.m	Modification from the validation copy that plots CLvAoA for all inputted airfoils at a given Reynolds number to determine stall angles	10B.3
Airfoil_Analysis_Comparisson_Plots_CL_SD7003.m	Modification from the validation copy that plots CLvAoA and CL/CDvAoA for airfoil SD7003 at given intervals of Reynolds number with greater resolution	10B.4
Airfoil_Analysis.m	Script to perform lift, mass, velocity calculations and plot results for chosen airfoils explored in chapter 6.4.2 .	10B.5

4.2.1 Comparison of S1223 airfoil in Earth's Atmosphere

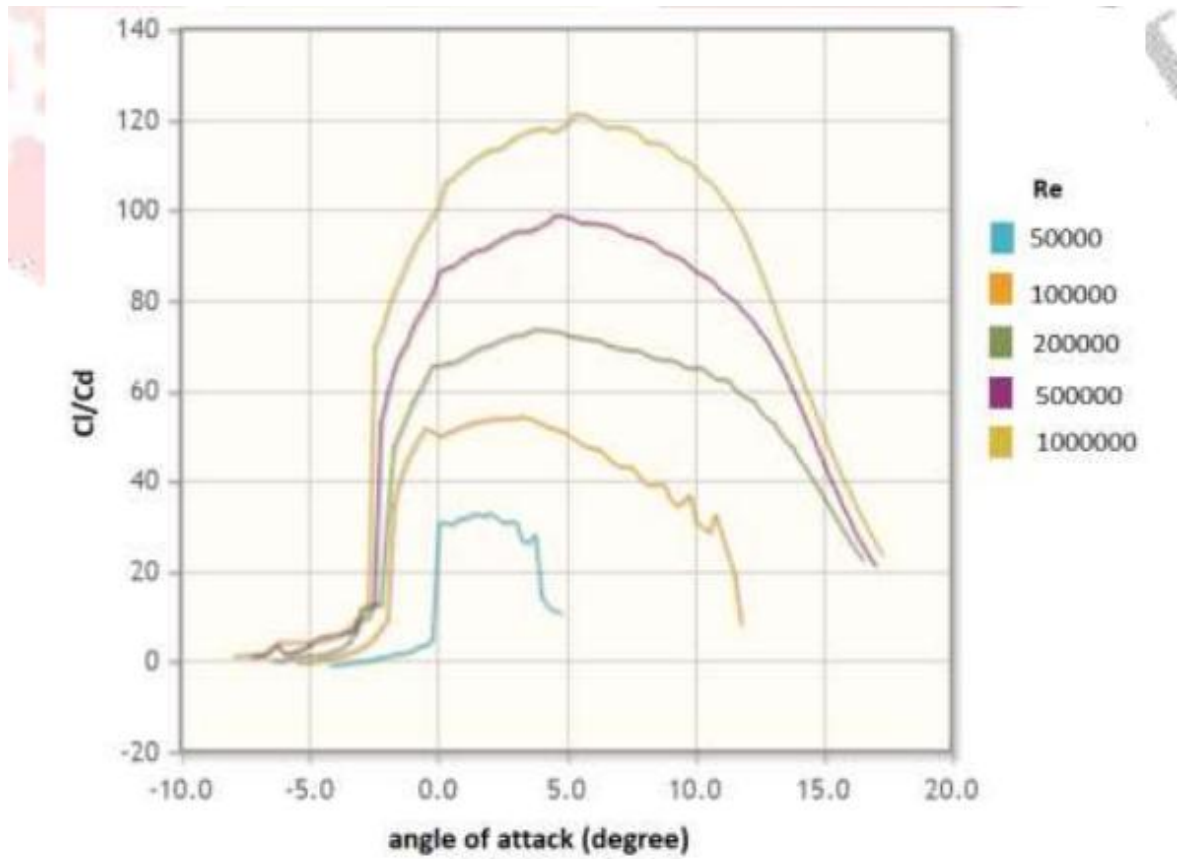


Figure 9: C_l/C_d polar for S1223 computed by xfoil and varying fixed Reynolds values (Lakdawala & Shaikh, 2018)

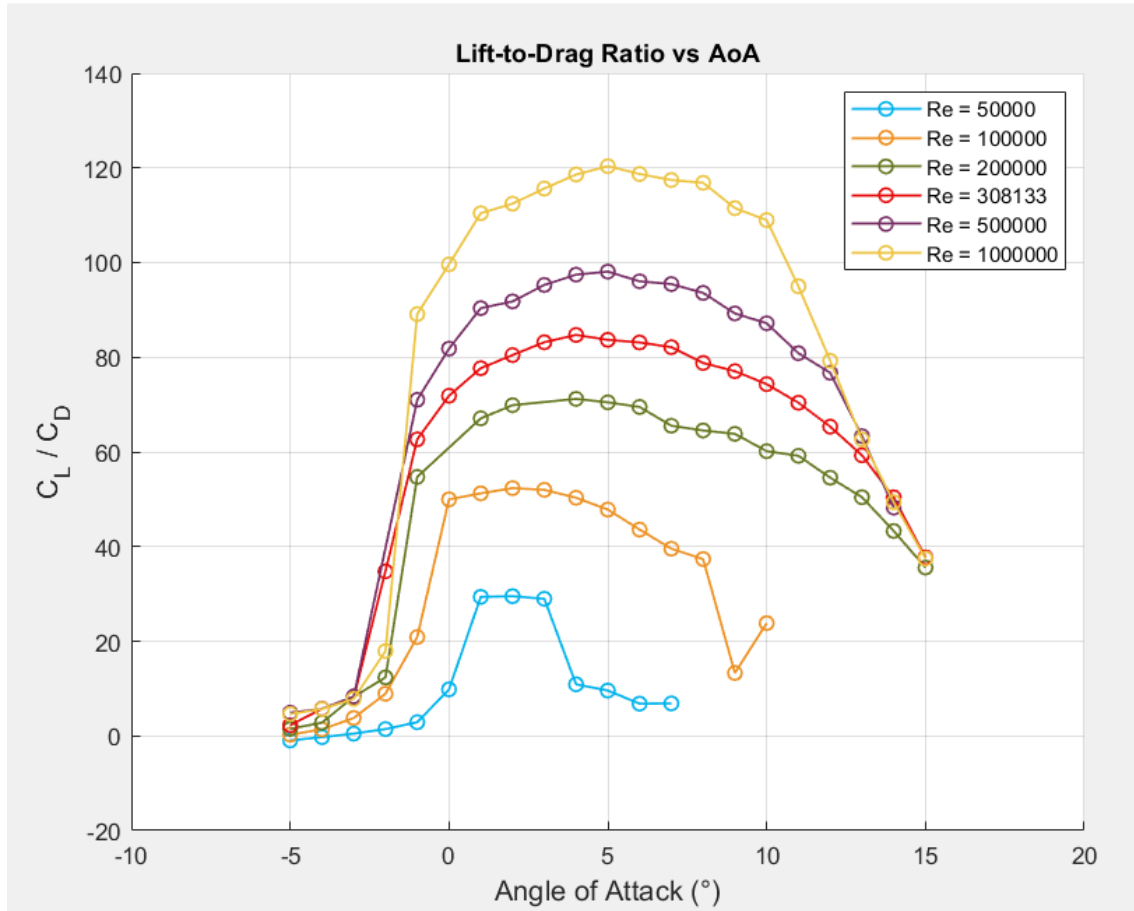


Figure 10: C_L/C_D polar for S1223 computed by xfoil using custom MATLAB script `Airfoil_Analysis_Validation_Copy.m`

Figure 10 is the resultant plot from the `Airfoil_Analysis_Validation_Copy.m` MATLAB script aimed at replicating the results of **Figure 9** at the five fixed Reynold number values (50 000, 100 000, 200 000, 500 000, 1 000 000). An additional red line depicts the predicted data for a calculated Reynolds number of 308 133 using **Equation 1** and the following input values:

- $\rho = 1.225$ [kg/m³] (Earth Sea level)
- $V = 15$ [m/s]
- $C = 0.3$ [m]
- $\mu = 1.789\text{e-}5$ [Pa s] (Earth air at 15 °c)

There are minor discrepancies between the plotted data **Figure 9** and **Figure 10**, most notably the additional data produced for $Re = 50\,000$, and the abnormally low data point produced for $Re = 100\,000$ at $AoA = 9^\circ$. These discrepancies occur

at relatively large angles of attack where flow separation is much more prevalent and xfoil's simulations become less reliable and more prone to convergence failures as seen below in **Figure 11**.

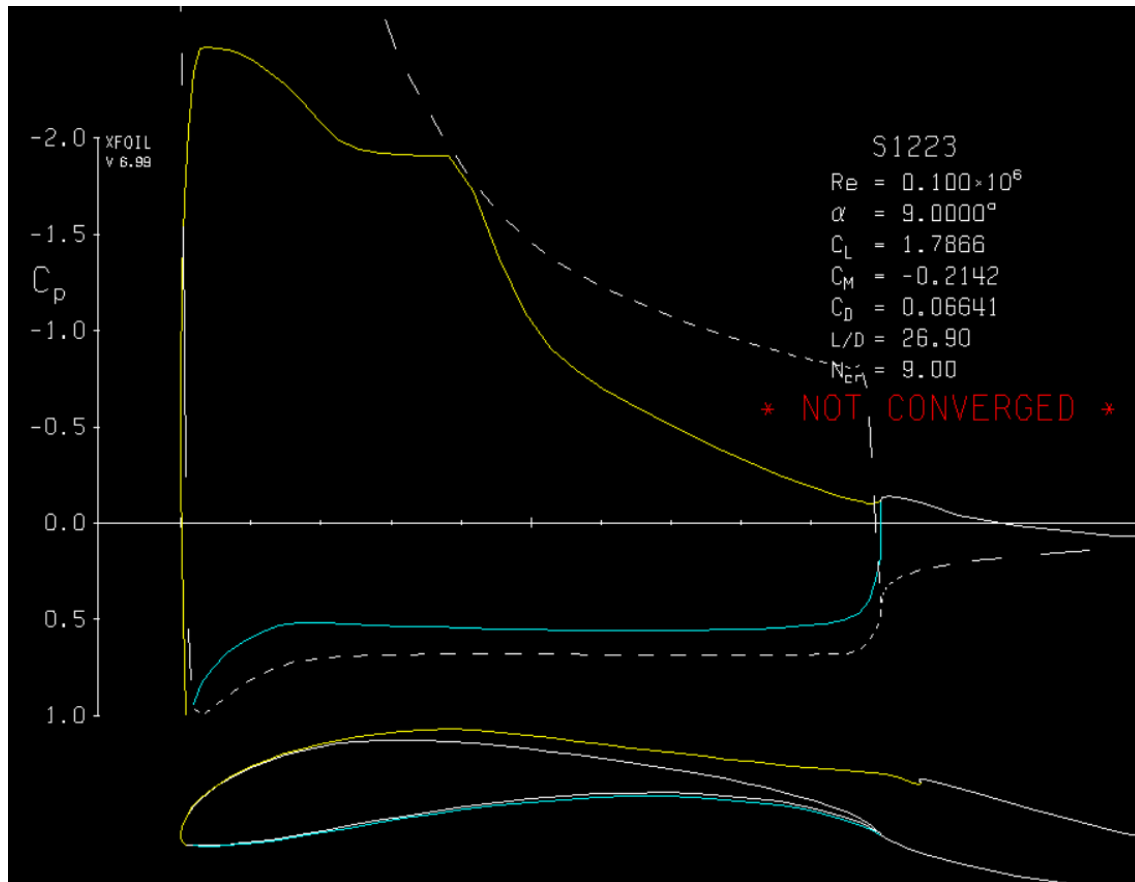


Figure 11: xfoil plot for Re=100 000 at Alpha=9 (Not Converged)

As stated in the xfoil user guide: “If convergence is not achieved within this limit, ALFA or CL can be issued as often as needed (most easily with “!”), with another set of Newton iterations being performed each time.” (Drela & Youngren). After several re-executions of the simulation, xfoil managed to converge, as seen in **Figure 12** below. By increasing the iterations, the number of convergence issues on the first alpha sweep simulation can be reduced.

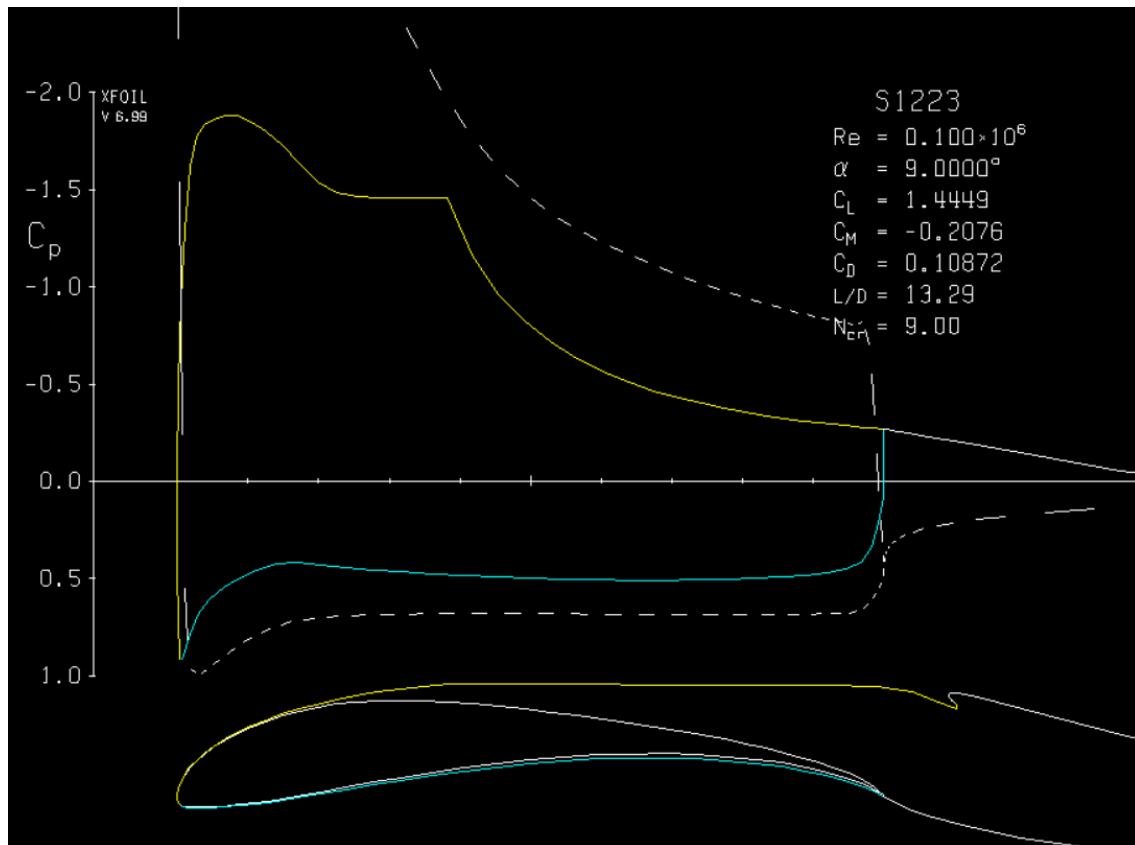


Figure 12: Xfoil plot for $Re=100\ 000$ at $\text{Alpha}=9$ (Converged)

4.2.2 Calculating wing surface area

Since Reynolds number is proportional to the relative velocity of the air to the vehicle as seen in **Equation 1**, the xfoil simulation can be run for an airfoil at varying velocities. The C_L data produce for each velocity can then be used in a rearranged version of the lift equation, **Equation 2**, in order to calculate the required wing surface area to negate the acceleration due to gravity, since for stable and level flight the lift force must be equal to the weight of the vehicle.

5 Martian Aerial Exploration Validation Experiment (MAEVE) Design Concept

MAEVE is an experiment to prove the feasibility of using fixed wings within the Martian atmosphere to allow for faster relocation of a vehicle, or sustained flight for aerial exploration and monitoring. Furthermore, it could be used to map out terrain ahead of robotic or human exploration, like the ingenuity rotorcraft, but at a much larger scale.

This chapter analyses the requirements and necessary components for such a system, as well as an overview of a possible mission plans in the Hellas basin. The airfoil selection and wing design follow in **chapters 6** and **6.4.3** respectively.

Directly below are 2 sketches for the proposed validation experiment design from a side view (cross section of the wing); **Figure 13** is a visual representation of the design landed on the Martian surface, **Figure 14** is a visual representation of the forces acting on the vehicle during steady level flight.

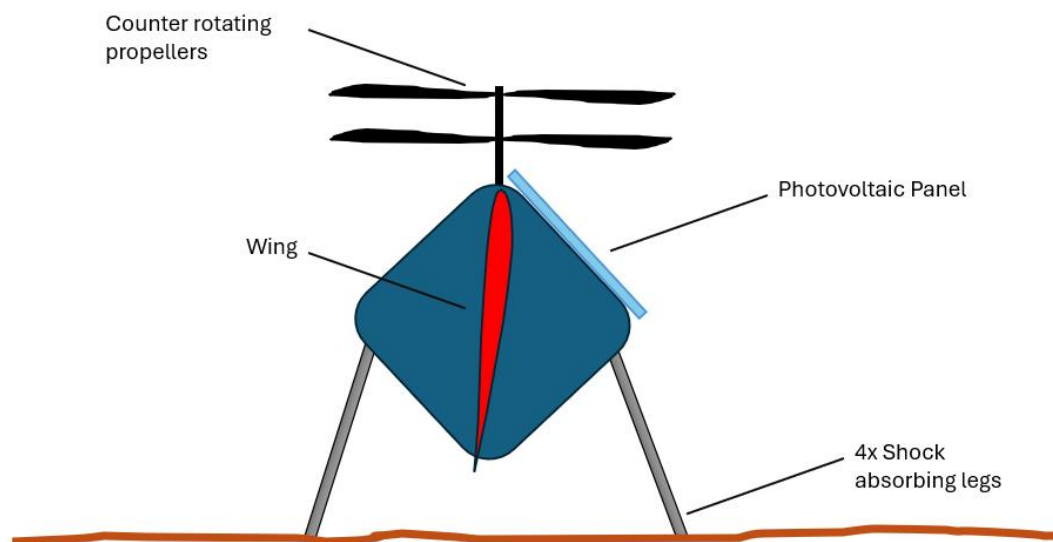


Figure 13: MAEVE preliminary design, annotated diagram of vehicle landed on Martian surface (Not to Scale).

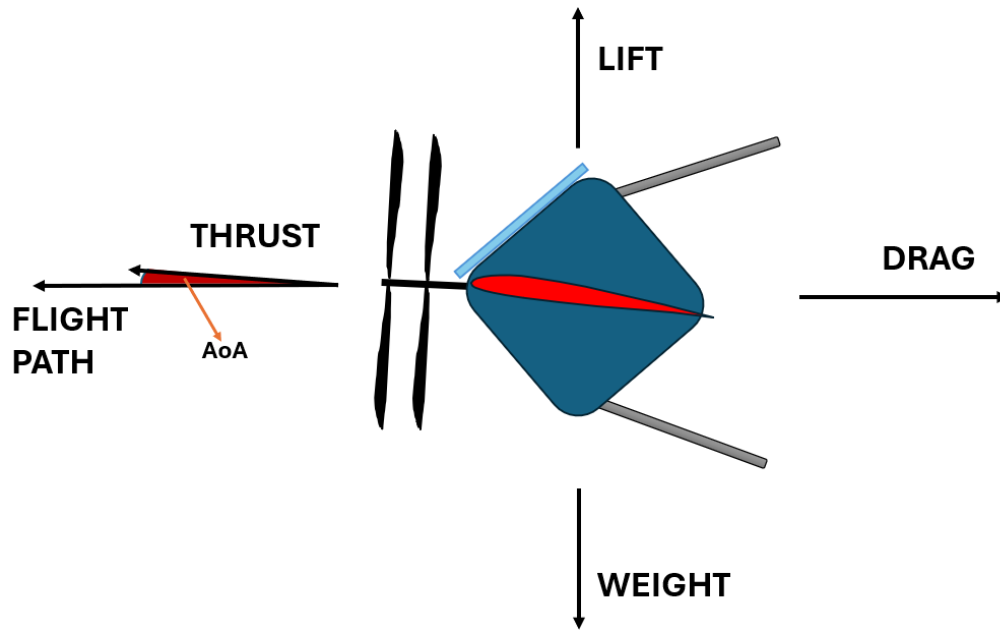


Figure 14: MAEVE preliminary design, force diagram of steady and level flight at constant speed (Not to Scale).

5.1 System Overview and Requirements

The original constraints for this vehicle are to aim for a mass of 5kg and not to exceed 10kg. The main body is set to be a cube with side lengths of 0.3m with 2 counter rotating co-axial rotor blades to provide vertical and horizontal acceleration. During flight the vehicle would tilt over to provide sufficient horizontal acceleration to maintain a constant velocity. The wing is expected to fully support the weight of the vehicle allowing the propellers to focus on purely horizontal acceleration and the estimated wing dimensions are discussed in **chapter 7: Wing Design**. In accordance with requirements VWR-001 and VWR-004, each wing should not exceed 2 meters in length and should be separated into no more than 4 deployable segments (hence maximum 50cm segments).

It is worth noting that flight time/range requirements have not been included as this vehicle is intended to validate the use of wings, with the limits of the system being pushed gradually over multiple flights. The expected maximum flight time should be maximised, while prioritising the reliability and functionality of all other systems.

Table 3: Table of preliminary requirements for the MAEVE.

AirFoil Reqs (AFR), Vehicle Capability Reqs (VCR) and Vehicle Wing Reqs (VWR)

ID	Requirement	Rationale
AFR-001	Airfoil shall have a chord length of 0.4m	Largest round number that can fit along the diagonal of the dimension requirement (VCR-004)
AFR-002	Airfoil shall exhibit smooth/gradual stall behaviour	Wings must be stalled in order for vehicle to transition to VTOL
VCR-001	Total vehicle mass shall not exceed 10kg	Validation Experiment that must remain light weight with minimal scientific equipment onboard
VCR-002	Battery shall be able to power critical systems for 10 sols without recharge	Safety margin (2x) on the maximum expected duration of localised dust storms (~5 sols). 3.2.1
VCR-003	Solar panel(s) shall be equipped with at least 2 methods of dust removal	Hellas Basin is one of the dustiest regions on Mars, the mission relies on a small solar panel functioning throughout. 3.2.1
VCR-004	The main body of the vehicle shall be restricted to a cube with sides of 0.3m	Vehicle must remain compact as it is a validation experiment,
VCR-005	The Propellers shall have a combined thrust to weight ration of at least 1.2	Vehicle must be able to lift its own weight to allow for VTOL

VWR-001	Length of a single wing shall not exceed 2 meters	Stability and balance issues with excessively long wings
VWR-002	Wings shall produce sufficient lift to maintain level flight at a predetermined optimum velocity	At the selected airfoils optimum velocity, the wing must be able to support the weight of the vehicle
VWR-003	The wings shall be able to withstand 2 times the expected peak force acting on them	Unpredictable changes in wind speeds, temperature and air density can cause increased stress on the wings and attachment points
VWR-004	Each wing shall be separated into no more than 4 segments	Minimise complexity and airfoil dimension variation while allowing for a more compact launch configuration

5.2 Flight Plan for Hellas Basin

As thoroughly discussed in **chapter 3: Martian Atmospheric Conditions**, the Hellas basin is one of the most desirable locations in terms of air density and air viscosity due to its low elevation (up to 8km lower than surrounding areas). It does, however, also have a higher concentration of dust which often contributes to the start of global scale dust storms, as well as reduced sunlight at the surface which explains why very few missions have ever been targeted for that region.

Having an aerial vehicle in that region would mean being able to map out or survey large swaths of land at a higher resolution and regularity than current satellite can, both before and after a dust storm to study the formation, behaviour and dissipation of Martian storms. Additionally, the vehicle can be landed in areas of specific interest to ‘ride out’ the storm and observe local changes. By landing

the vehicle such that the angled solar panel is now facing up and northwardly, it compensates for the solar zenith angle variation caused by being at a low latitude.

5.3 Subsystems

As with any vehicle, a series of subsystems must work in tandem for proper operations. The key subsystems for this validation experiment to function would be: Electrical energy production and handling, propulsion and vehicle control, payload (including optical cameras) and survivability.

5.3.1 Electrical Energy

The vehicle must be powered, with the only 2 sources of energy feasibly available for a mars mission being solar or nuclear; the latter of which would be simply too heavy and expensive for this design. A single solar panel could be oriented such that the drone can land facing the same direction (roll angle relative to planet) and allow the solar panel to charge during the day at an optimum angle, determined by the zenith angle of the sun in the proposed region.

Additionally, a battery is required to provide enough power for flight, as well as support the vehicle's sub systems during daily ground operations such as but not limited to communication, heating, data collection and solar panel de-dusting. Additionally, the battery must be able to maintain power to all these systems throughout the duration of a local dust storm, with a method of shutting down for longer global dust storms and safely start up again should the mission exceed expected lifespan.

5.3.2 Propulsion and Lift

All of the vehicle's thrust will come from a pair of propellers using a co-axial counter rotating system similar to that of Ingenuity. The thrust to weight ratio of the entire vehicle must be greater than 1 to allow for vertical take-off and landing (VTOL) maneuverers.

The propellers would be driven by an electrically powered motor with large throttle capability as minimal power would be required during level flight to maintain the horizontal velocity.

5.3.3 Optics and Payload

A range of scientific equipment can be included within the vehicle as long as the primary system mass and dimension budgets are respected and prioritised. Such equipment should include at least one optical camera to be used both during flight and landed on the surface. Additional equipment can include temperature sensors, pressure sensors and optical depth sensors to continuously measure changes in the environment, especially in the days leading to and during a dust storm.

If the vehicle performs flights around the same time each day, sensor data could more easily be correlated and images would have similar lighting conditions. By scheduling flights for either the morning or evening, local noon can be used to charge the battery most efficiently with the solar panel optimally angled to match the known solar zenith angle.

5.3.4 Survivability

A common mission ending condition on Mars is decreased solar panel efficiency due to dust accumulation over time. An aerial vehicle brings an advantage to this issue as the propeller wash can ‘blow’ dust off the surface of the solar panels if components are aligned correctly. This can greatly increase the lifespan of the drone, however, it should **not** be the primary method of dust clearing and rather should be considered a redundancy/backup solution to alternate methods like electrostatic or vibrating solar panel surface, or a retractable cover, ideally with a ‘opened cover’ failure mode.

5.3.5 Flight Controls

Using control surfaces on the last wing segment would maximise the moments of the centre of mass in order to induce rolling or pitching moments. Additionally, winglets on the ends of the wings could provide roll stability and contain control surfaces that contribute to yawing moments. Another method of inducing yawing moments would be by using split drag rudders, which are wingtip clamshell-like control surfaces that deploy on one wing and not the other to produce drag, inducing yaw. This method has been validated on tail-less aircraft designs such as the B-2 stealth aircraft (Britt, Volk, Dreim, & Applewhite, 1999).

Alternatively, any or all 3 axes of rotation could be controlled by either gimbling the propeller system for pitch and yaw control or adjusting the counter rotating rpms to induce a roll. This method would be crucial to low-speed controllability such as during hover and VTOL manoeuvres.

5.4 Summary of Vehicle Design

MAEVE is a fixed-wing VTOL validation platform based around a cubic fuselage of length 0.3m. It uses a pair of coaxial, counter rotating propellers to provide both vertical acceleration for take-off and landing, and horizontal acceleration for steady flight. The vehicle target mass is 5kg with a hard limit at 10kg and is to operate within the Hellas Basin region due to its advantageous air density and viscosity conditions relative to the Martian mean. **Figure 15** below is an annotated diagram of the top-down view of the vehicle with approximated dimensions in accordance with the requirements set out in **Table 3**.

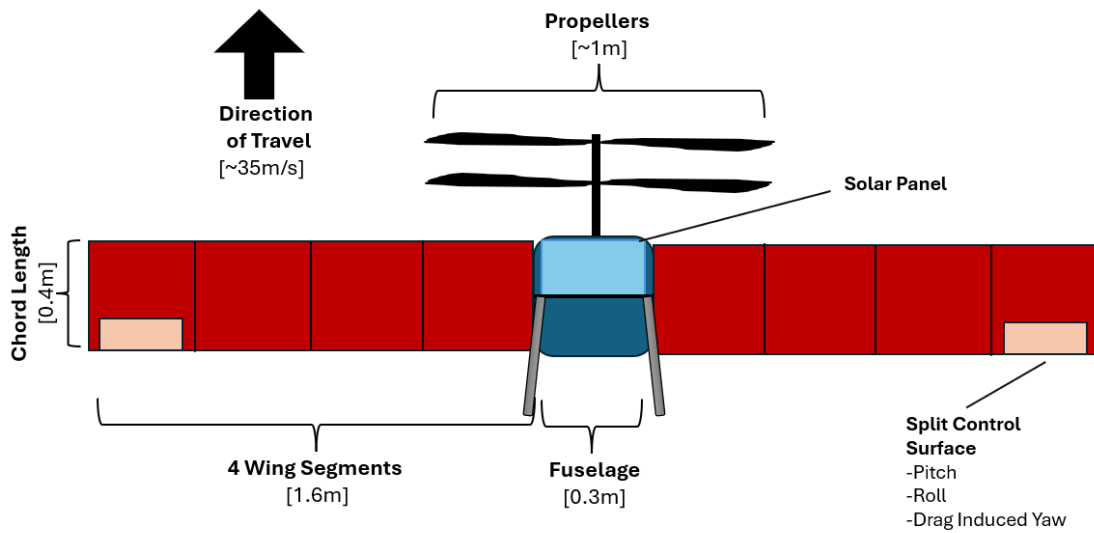


Figure 15: MAEVE preliminary design, annotated top-down view diagram of vehicle in flight with approximate dimensions (Not to Scale).

The vehicle is expected to have a total wingspan of no more than 4.3m: wings of 2m each in addition to the 0.3m wide fuselage. The wings are to be separated into segments that deploy via internal telescopic rods that are extended using hot gas reactions and locked in place once fully extended; the purpose of segmenting the wings is to minimise stow dimensions to make the vehicle more versatile in terms of ridesharing another payload to Mars.

The vehicle propulsion system will be powered by an electric battery, recharged by a solar panel on one side of the vehicle which will always be oriented towards the north in accordance with the sun's mean zenith angle in Hellas basin. Additionally, the solar panel will require 2 methods of dust removal, including the use of propwash from the propeller system to validate its effectiveness. The second method could be a physical cover, an electrostatic or a vibrating layer.

6 Airfoil Tradeoffs

Chapter 5 provides an in-depth analysis of several well studied low Reynolds number airfoils that are in line with the requirements set in **chapter 5.1**, provided again in the following subsection below. The analysis is conducted at low speeds ($v=20\text{m/s}$ and $v=30\text{m/s}$) and then repeated again at high speeds ($v=40\text{m/s}$ and $v=50\text{m/s}$) as additional airfoil analysis is required in accordance with the flow chart below due to velocity (flight conditions) being the limiting factor.

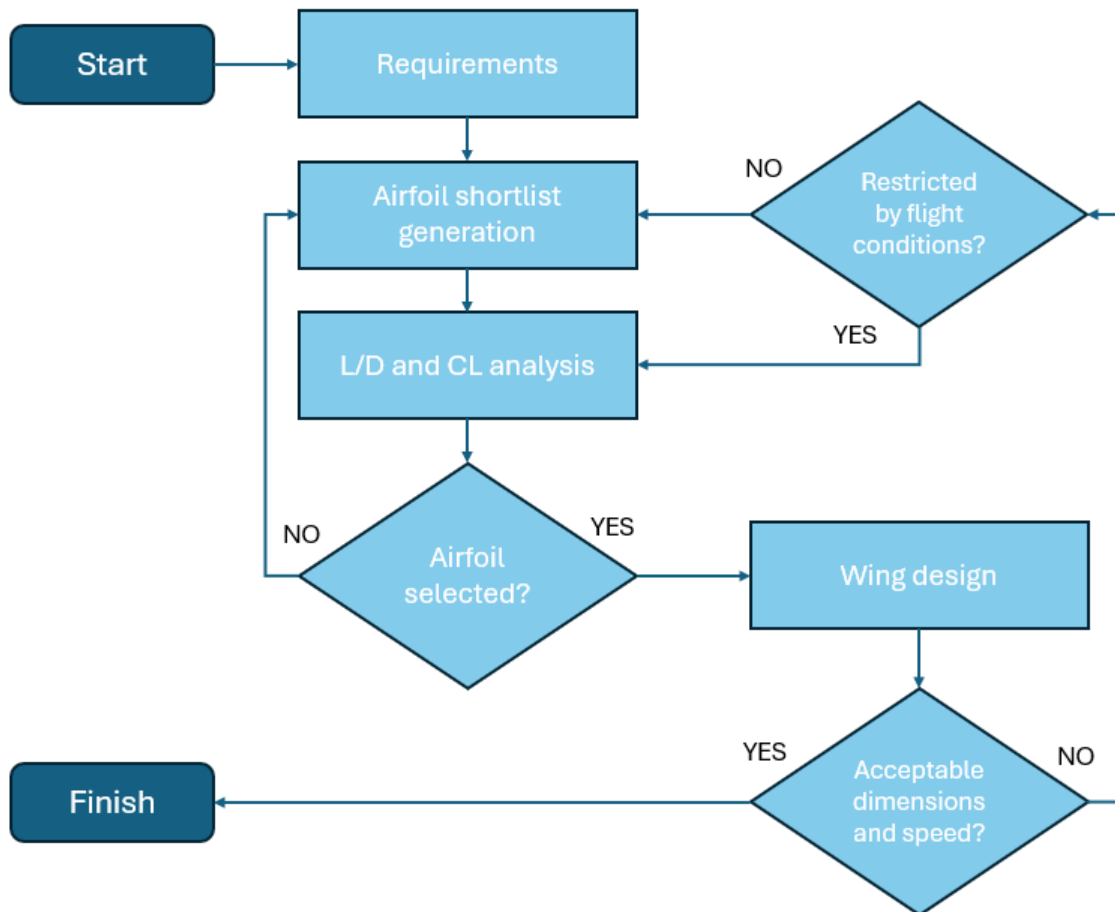


Figure 16: Flowchart representing airfoil selection and wing design process

6.1 Airfoil Requirements

There are 2 main requirements in the airfoil selection process, copied into the table below:

Table 4: Copy of the Airfoil Requirements from the complete table of requirements (Table 3).

ID	Requirement	Rationale
AFR-001	Airfoil shall have a chord length of 0.4m	largest round number that can fit along the diagonal of the dimension requirement (VCR-004)
AFR-002	Airfoil shall exhibit smooth/gradual stall behaviour	Wings must be stalled in order for vehicle to transition to VTOL

In order to maximise the Reynolds number, and hence the chances of each of the airfoils working properly in the Martian atmosphere, there are 4 variables that can be changed according to **Equation 1: Reynolds Number**. Air density and air viscosity are considered constants that are set prior to simulation depending on the region (**Table 6**). Velocity is easily variable and is the main factor being analysed towards the end of this chapter. The Chord length can also vary but for simplicity it has been set to a constant of 0.4m so it can fit appropriately within the fixed dimensions body of the vehicle: Hypotenuse of a 0.3m x 0.3m square side is roughly equal to 0.4m.

6.2 Shortlist

Table 5 below provides a shortlist of the 6 airfoil shapes that have been selected for their use in published research of low Reynold number airfoils. In addition to the low Re airfoils, a small selection of ‘cambered thin plate’ have been added under custom names to complement previous research on thin plates for low Re numbers (Vuong, Nguyen, & Le, 2025). Rationale behind the selection process is covered in **chapter 2.3**

Table 5: Airfoils shortlisted for their beneficial characteristics, initially discussed in chapter 2.3: Prior work on airfoils for low density atmospheres.

Airfoil	Notes / Reference
S1223	Well documented, low Reynolds number airfoil, ideal for validation purposes and baseline data for following airfoils
Eppler 387	(Aprovitola, Iuspa, Pezzella, & Viviani, 2024)
SD7003	(Aprovitola, Iuspa, Pezzella, & Viviani, 2024)
NACA 4412	(Vuong, Nguyen, & Le, 2025) Thickness = 4% chord
NACA 6412	(Vuong, Nguyen, & Le, 2025) Thickness = 6% chord
E171-il	Symmetric low Reynolds number airfoil
CP_6_5_r211	Cambered plate airfoil Camber = 6% chord Thickness = 5% chord Radius = 2.11
CP_8_5_r16	Cambered plate airfoil Camber = 8% chord Thickness = 5% chord Radius = 1.6
CP_10_5_r13	Cambered plate airfoil Camber = 10% chord Thickness = 5% chord Radius = 1.3

Note: all .dat files for the airfoil geometries can be found in either the UIUC Airfoils Database (Group, n.d.) or (AirFoil Tools, n.d.)

6.3 Simulation Conditions

The Reynolds number is calculated at each key region discussed in **chapter 3.1**. The approximate air density and viscosity data are extracted from **Figure 3** and **Figure 5** respectively and summarized in the second and third columns of **Table 6** and **Table 7** below:

Table 6: Calculated Reynolds number for low-speed flight at each of the 5 predesignated regions using Equation 1.

(Chord length = 0.4m | V = 20m/s & V = 30m/s)

Region	Air Density	Air Viscosity	Re at V=20m/s	Re at V=30m/s
Tharsis Rise	1.00E-02	1.10E-05	7.27E+03	1.09E+04
Chryse Planitia	1.70E-02	1.20E-05	1.13E+04	1.70E+04
Southern Highlands	1.30E-02	8.00E-06	1.30E+04	1.95E+04
Argyre Basin	2.50E-02	8.10E-06	2.47E+04	3.70E+04
Hellas Basin	3.20E-02	9.30E-06	2.75E+04	4.13E+04

The Reynolds numbers are initially calculated for each region at 'low speed' (**Table 6**), with velocities of v=20m/s and v=30m/s. The chord length (c) is set to 0.4m in accordance with requirement **AFR-001** as it is just under the maximum permissible length to fit within the dimension limits of the vehicle's main body, requirement **VCR-003**.

Table 7: Calculated Reynolds number for high-speed flight at each of the 5 predesignated regions using Equation 1.

(Chord length = 0.4m | V = 40m/s & V = 50m/s)

Region	Air Density	Air Viscosity	Re at V=40m/s	Re at V=50m/s
Tharsis Rise	1.00E-02	1.10E-05	1.45E+04	1.82E+04
Chryse Planitia	1.70E-02	1.20E-05	2.27E+04	2.83E+04
Southern Highlands	1.30E-02	8.00E-06	2.60E+04	3.25E+04
Argyre Basin	2.50E-02	8.10E-06	4.94E+04	6.17E+04
Hellas Basin	3.20E-02	9.30E-06	5.51E+04	6.88E+04

A further analysis is required at higher speeds using Re numbers calculated in **Table 7 above** at velocities of v=40m/s and v=50m/s. The chord length remains at 0.4m and the air density and air viscosity values remain the same for each key region.

6.4 Performance of Shortlisted Designs in Martian Atmosphere

All simulations run in this chapter have been run for 2 of the 5 key identified regions: **Hellas Basin**, the region which provides the conditions for larger Re numbers due to the maximised air density, and the **Southern Highlands**, a region with more typical Martian atmospheric conditions allowing for more average Re values. Regions like Tharsis Rise that have even less suitable conditions for flight were not analysed but airfoil behaviour at high speeds could be approximated to low speed behaviour in the analysed region (i.e. Tharsis rise at 50m/s has a Re of **18,200**; Southern highlands at v=30m/s has a Re of **19,500**)

6.4.1 Lift to Drag Ratio (CL/CD vs AoA) at Low Speed

A CL/CD plot comparing all 9 shortlisted airfoils is produced for each of the calculated Reynolds numbers in **Table 6**, at $v=20\text{m/s}$ and $v=30\text{m/s}$, to determine the efficiency of the airfoil under different expected Reynold numbers, derived from flight at different velocities.

In **Figure 177** through to **Figure 20**, there are a few airfoils of particular interest, most notably airfoil **SD7003**; this airfoil has a tendency to plateau at its peak usually between an AoA of 4° and 6° , with the peak almost always exceeding the maximum CL/CD of the other non-plate airfoils. This behaviour is most apparent in the 30m/s simulation in Hellas basin (**Figure 188**) where the Reynolds number is the greatest.

Airfoil **E171-ii**, the symmetrical airfoil, shows an expected low efficiency at small AoA but in Hellas basin (**Figure 177 & Figure 188**), however, a large spike in airfoil efficiency occurs between 6° and 8° AoA. While the instantaneous CL/CD may exceed most other airfoils, it may be unrealistic for the vehicle to maintain such a precise AoA, especially with possible varying conditions throughout the flight such as winds and air density/temperature fluctuations. This 'spike' in efficiency also occurs for a few other airfoils, namely the **E387** and **NACA4412** airfoils.

Lastly, the 3 cambered plate airfoils, depicted by the lines with 'x' markers, all exhibit similar behaviours at separate intervals of AoA. This behaviour includes significant inefficiency ($\text{CL/CD} < 0$) at low AoA, followed by a sudden increase in efficiency at AoA larger than 6 degrees. Best seen in **Figure 177** and **Figure 198**, **CP_6_5_r211** (Blue) appears to maintain a consistent peak efficiency for a larger range of AoA, however **CP_8_5_r16** (Green) appears to achieve a slightly larger peak efficiency while maintaining consistency for a few degrees of AoA.

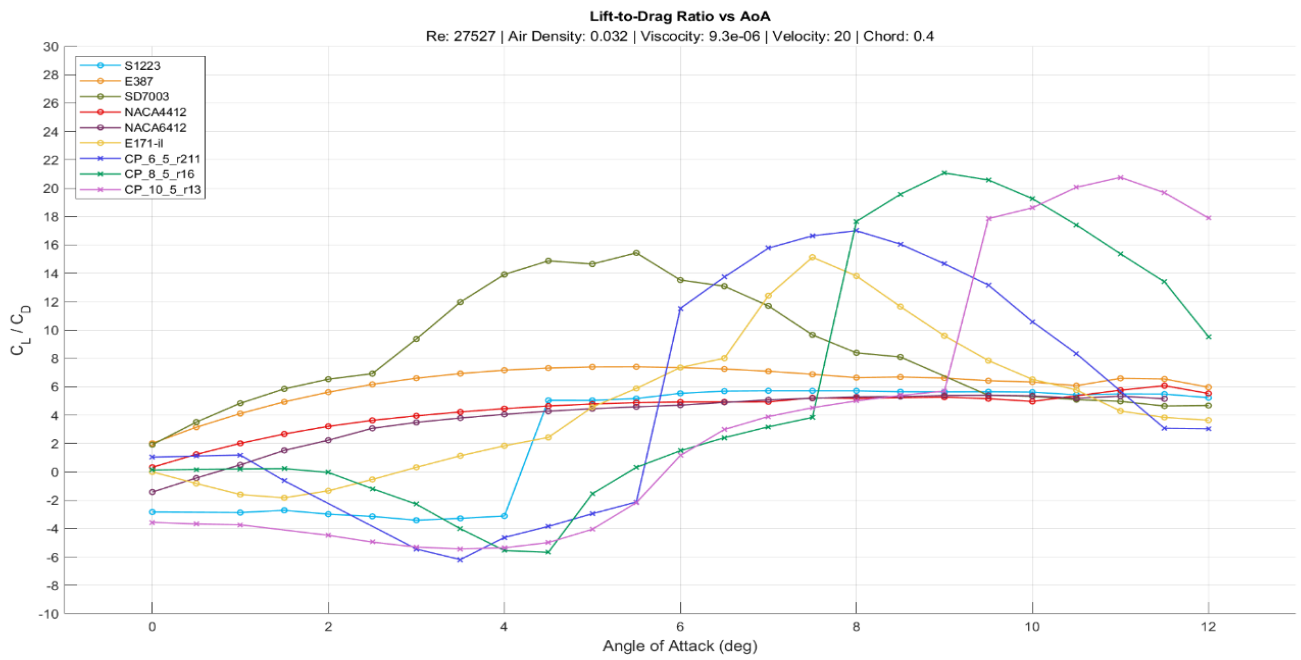


Figure 17: C_L/C_D against AoA in Hellas Basin at Velocity = 20m/s

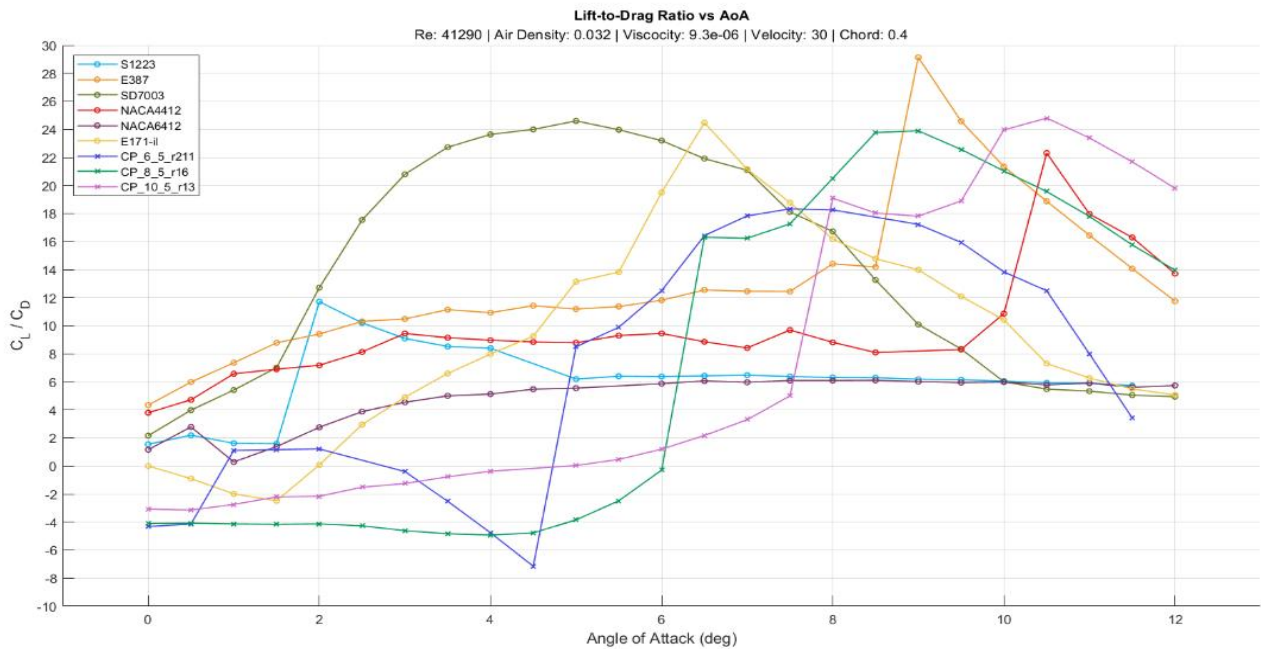


Figure 18: C_L/C_D against AoA in Hellas Basin at Velocity = 30m/s

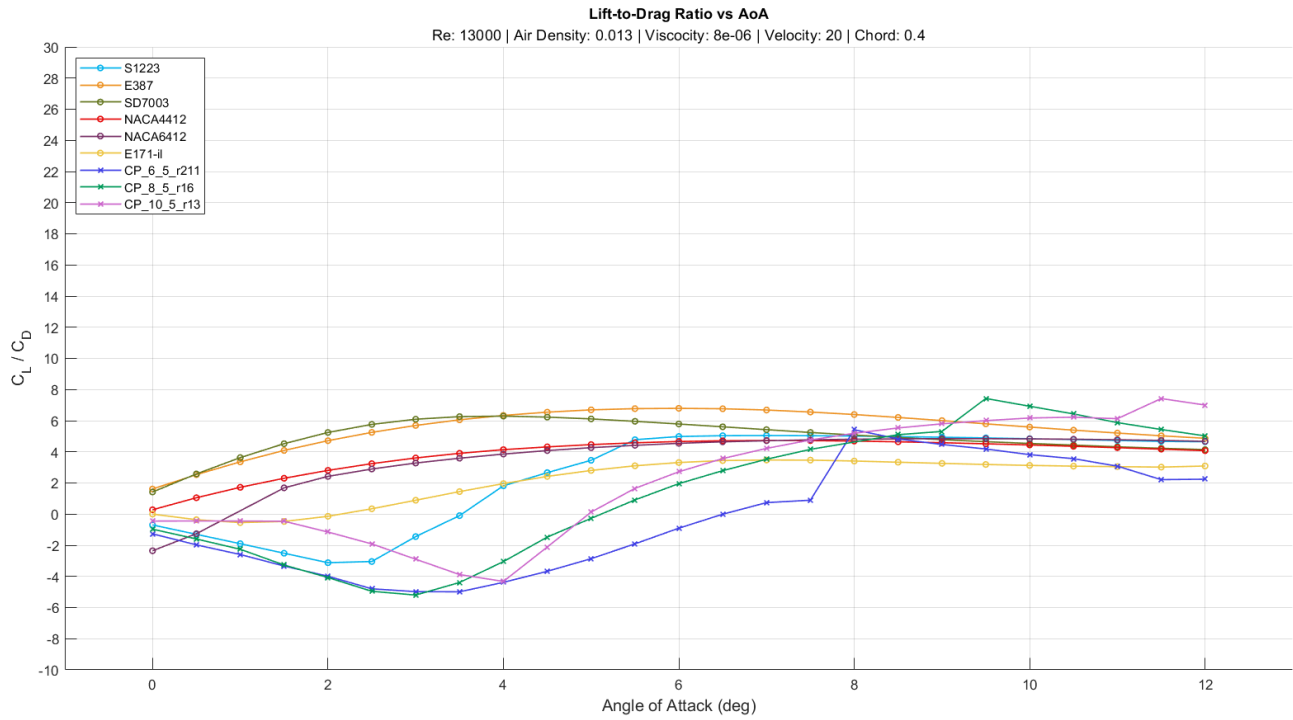


Figure 19: CL/CD against AoA in Southern Highlands at Velocity = 20m/s

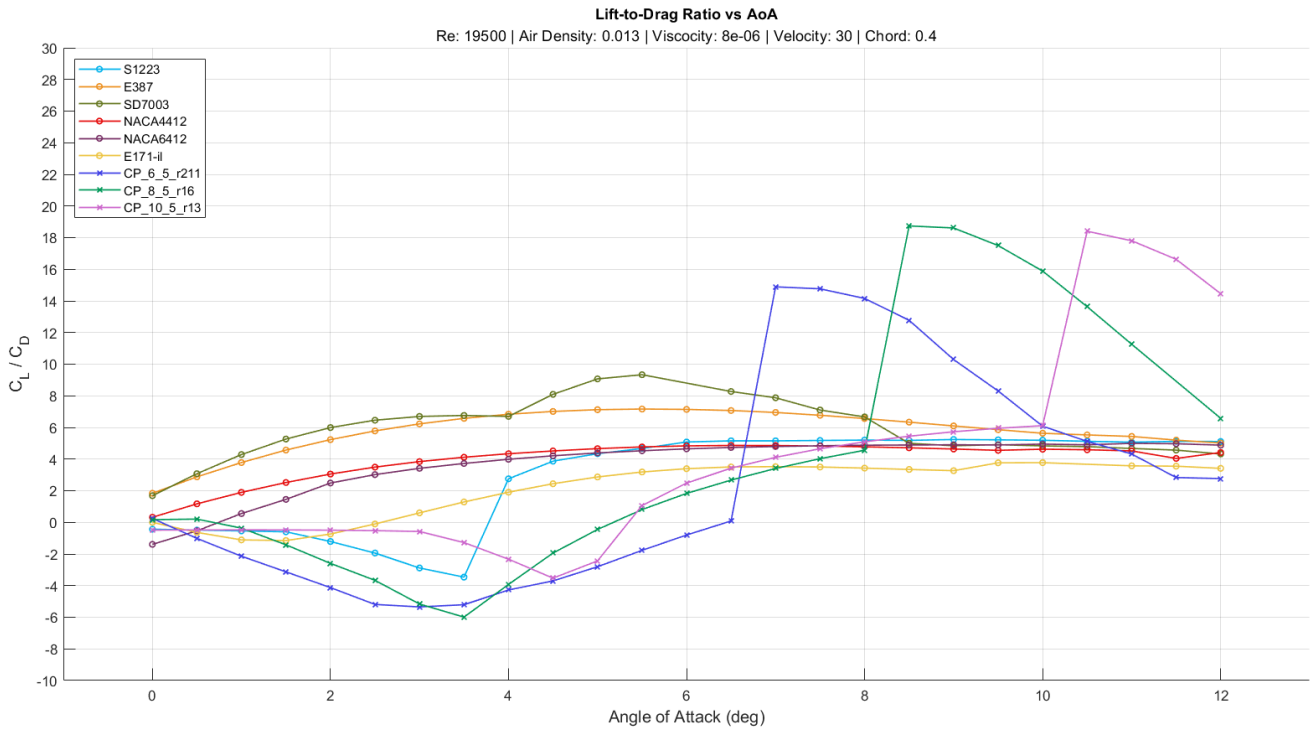


Figure 20: CL/CD against AoA in Southern Highlands at Velocity = 30m/s

6.4.2 Stall Behaviour (CL vs AoA) at Low Speeds

Stall behaviour is another important factor in airfoil design/trade-offs, whether the airfoil experiences a rapid or slow stall, and at what angle does the wing begin to stall. The stall angle of the airfoil can generally be approximated to where the CL vs AoA gradient becomes negative after the first CL peak ((FAA), 2023).

In **Figure 21** and **Figure 22**, the stall angle for a higher Reynold simulations at Hellas basin can be predicted for each of the airfoils. The **SD7003** airfoil exhibits a very gradual stall at around $8^\circ \pm 0.5^\circ$ AoA. In the Southern Highlands simulation, at $v=30\text{m/s}$ (**Figure 24**), stall once again occurs around 8° but this time a little more abruptly, suggesting better suitability at speeds above 30m/s . At $v=20\text{m/s}$ (**Figure 23**Figure 23), however, the gradient of CL/AoA does not become negative and instead continuously rises; this is likely due to the wing already being stalled under those conditions. This point is further proven by the lift to drag ratio at those conditions (**Figure 19**Figure 19) reaching a peak of only 6 at 4° AoA rather than $6^\circ - 8^\circ$.

In the case of the 3 cambered plate airfoils, **CP_6_5_r211**, **CP_8_5_r16** and **CP_10_5_r13**, they all experience quite rapid stalls at higher Reynold conditions (**Figure 21** and **Figure 22**), occurring at AoAs of roughly 9.5° , 10.5° and 12° respectively. When simulated in the Southern Highlands however, at $v=20\text{m/s}$ (**Figure 23**Figure 23) the 3 airfoils appear to plateau for a few degrees of AoA before experiencing a more gradual stall, and a similar but less pronounced plateau at higher speed (**Figure 24**Figure 24). This is because the coefficient of lift does not rise much higher than the baseline minimum the airfoil would operate at if the airflow were separated ($CL \sim 0.5$), as the airflow conditions for flight are simply not met. This is further compounded by the very low lift to drag ratio depicted for all airfoils under southern highland $v=20\text{m/s}$ conditions in **Figure 19**Figure 19 above.

The drone being designed is expected to be capable of transitioning from horizontal flight to a vertical orientation with 0 horizontal velocity in order to perform VTOL manoeuvres. In order to transition between the 2 states, the wing will have to transition past its stall angle so a more gradual stall would be beneficial to the stability and control of the vehicle.

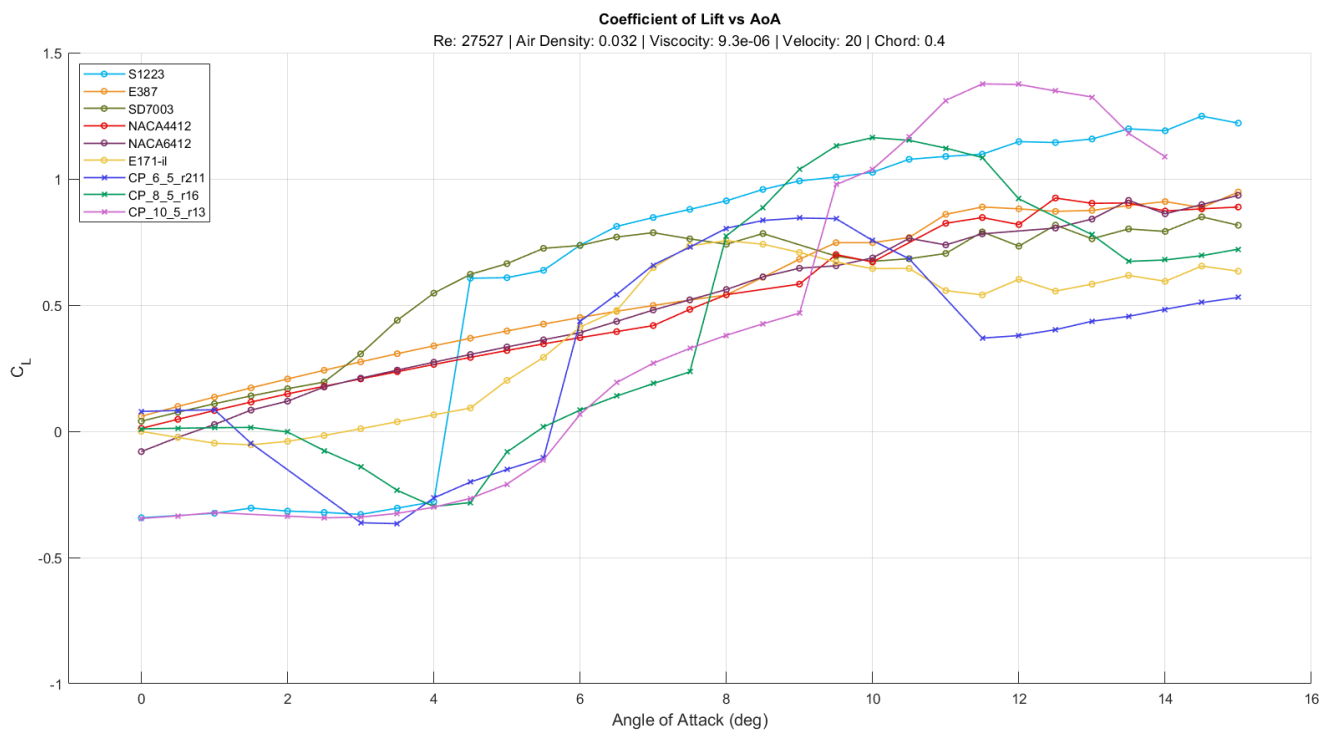


Figure 21: CL against AoA in Hellas basin at Velocity = 20m/s

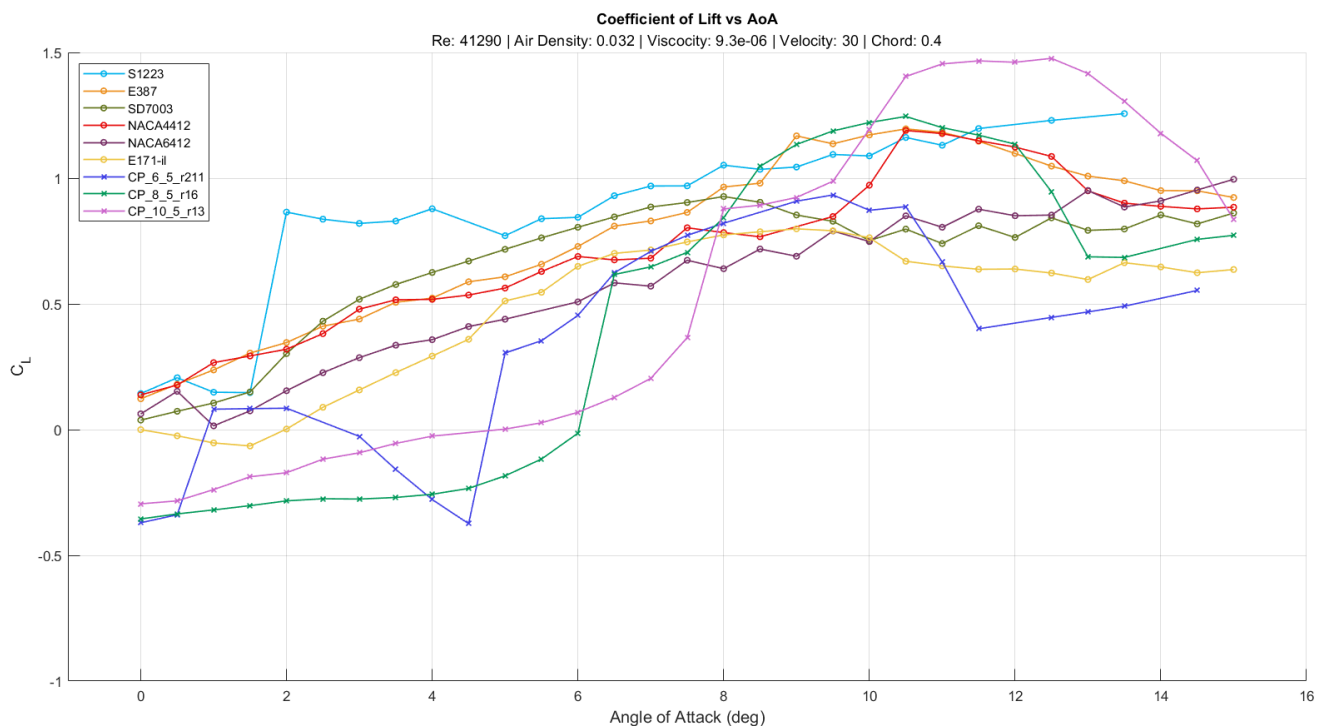


Figure 22: CL against AoA in Hellas basin at Velocity = 30m/s

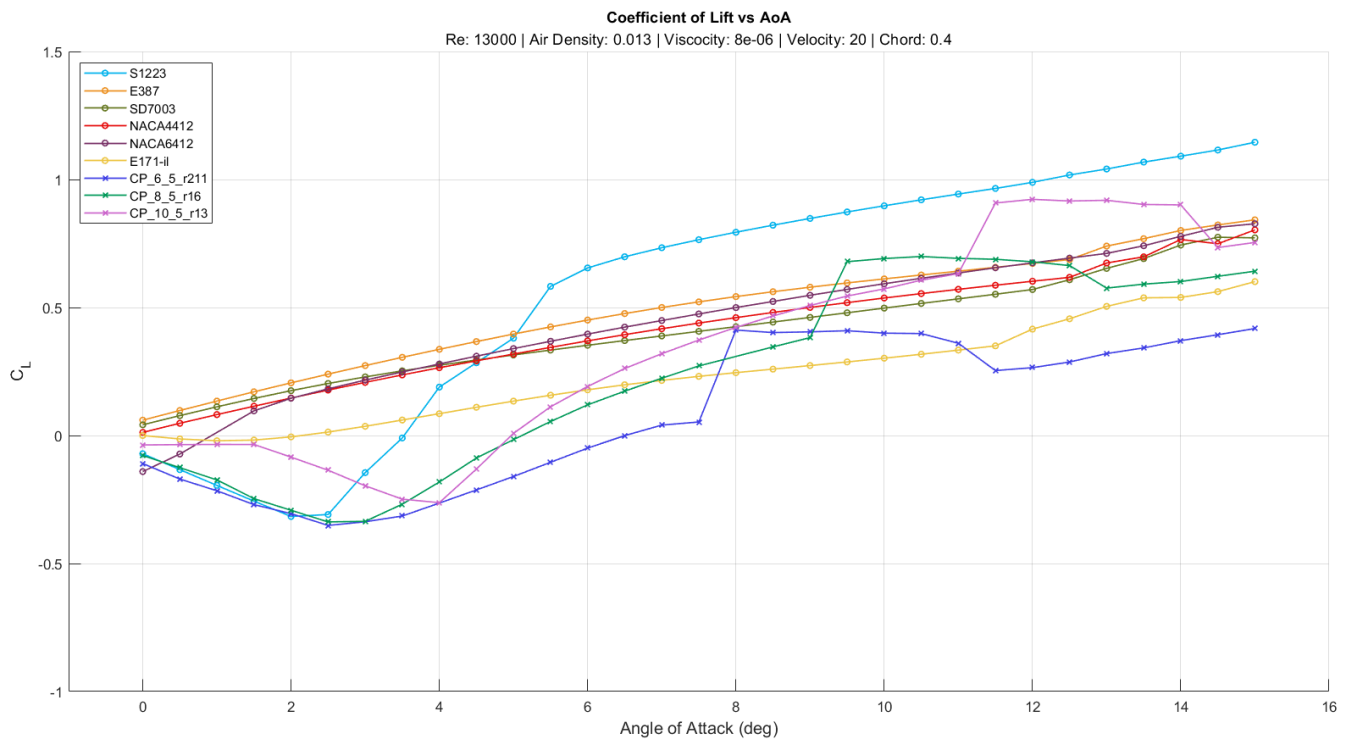


Figure 23: CL against AoA in Southern Highlands at Velocity = 20m/s

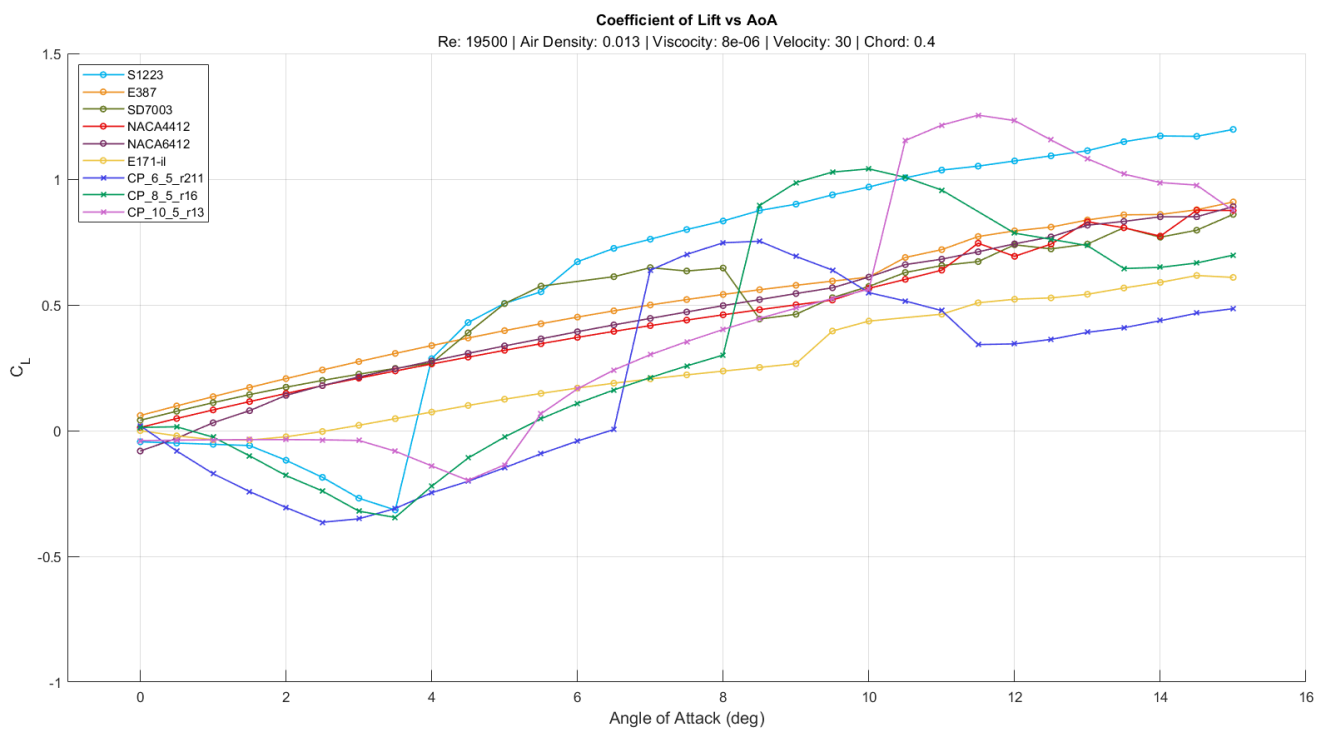


Figure 24: CL against AoA in Southern Highlands at Velocity = 30m/s

6.4.3 Further Analysis: Lift to Drag Ratio (CL/CD vs AoA) at High Speed

A CL/CD plot comparing all 9 shortlisted airfoils is produced once again for each of the calculated Reynolds numbers in **Table 7** for **Hellas Basin** and **Southern Highlands**, at $v=40\text{m/s}$ and $v=50\text{m/s}$. **NOTE:** the y axis for the following plots has been adjusted to accommodate the increased y-max values simulated.

Figure 255 and **Figure 266** represent the efficiency of the airfoils at velocities of 40m/s and 50m/s respectively in Hellas Basin. A similar trend is observed for the 3 airfoils discussed in depth in **6.4.1**, namely that the **SD7003** airfoil depicts a smooth plateau in the low AoA range of $\sim 3\text{-}7^\circ$, whereas, the **E387** and **NACA-4412** airfoils both experience large, short-lived, spikes in efficiency at 8.5° and 9.5° respectively.

There is, however, a discrepancy in the data produced for the high-speed Hellas basin simulations that does not appear on the lower speed data, the light blue line representing airfoil **S1223** shows a significant increase in efficiency at low AoA, surpassing that of the **SD7003** airfoil, which to this point has been the superior option. These two simulations are the highest Re number runs due to the maximised air density and velocity, with **Figure 255** representing data at $\text{Re}=55,000$, and a steady but rough plateau of L/D between 0° and 2° AoA; **Figure 266** represents data at $\text{Re}=68,800$ with a longer plateau of L/D between 0° and 4° AoA.

Strictly from an airfoil efficiency perspective, the **S1223** airfoil is better suited for higher Re conditions greater than 55,000 and the **SD7003** airfoil is better suited for Re conditions less than 55,000, while still being reliable at larger Re. General suitability would vary depending on the stall behaviour analysed in the following section.

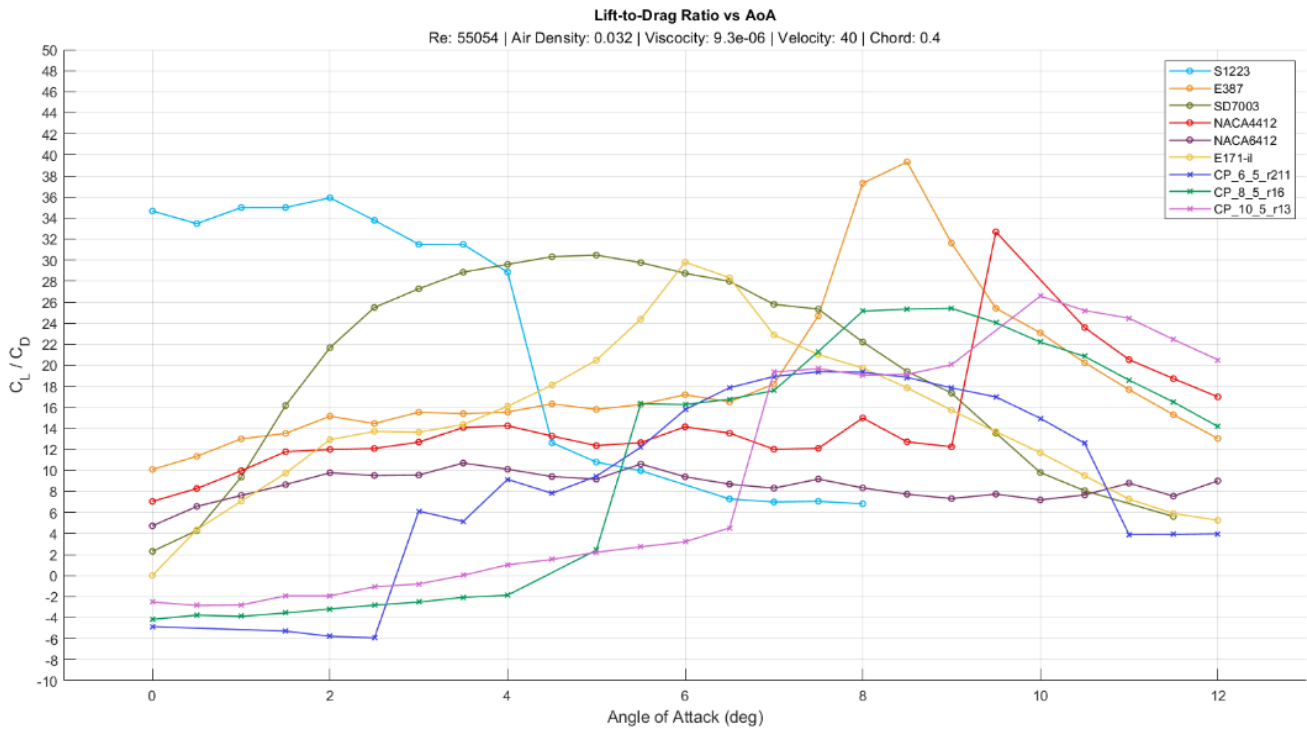


Figure 25: CL/CD against AoA in Hellas basin at Velocity = 40m/s

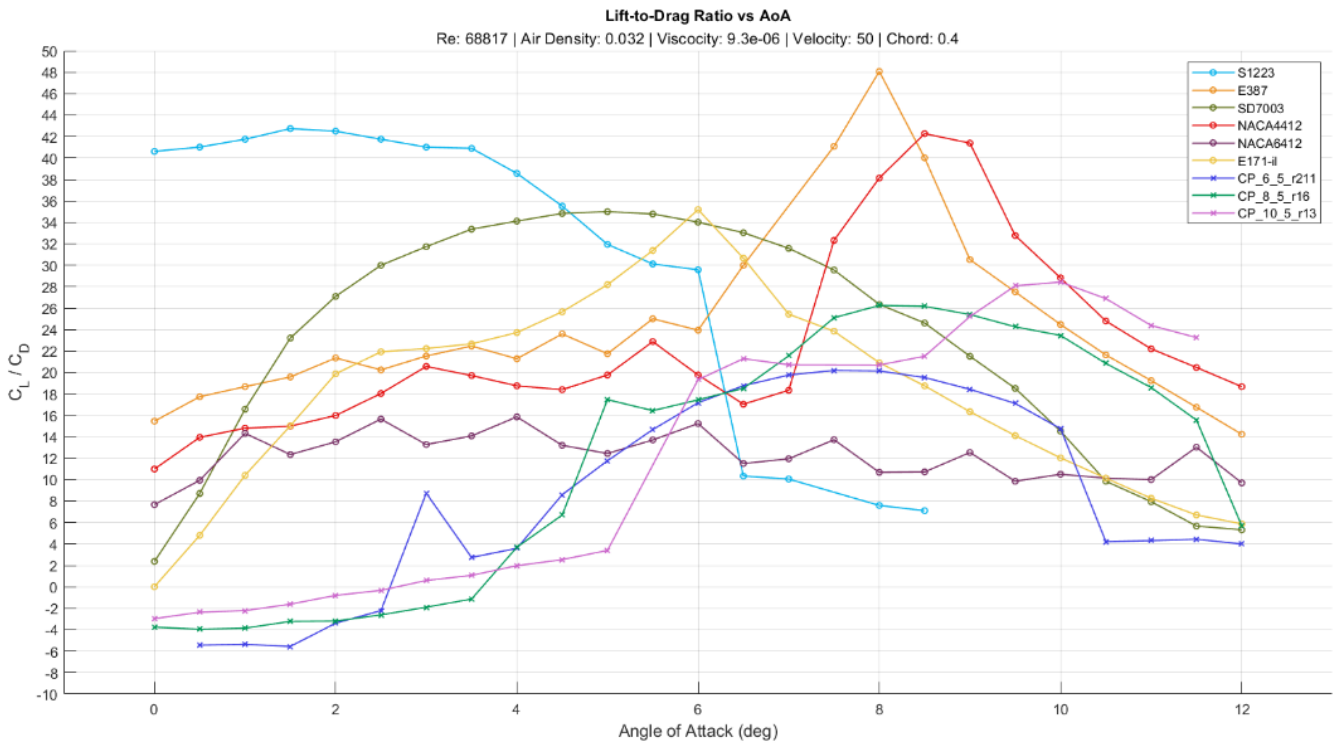


Figure 26: CL/CD against AoA in Hellas basin at Velocity = 50m/s

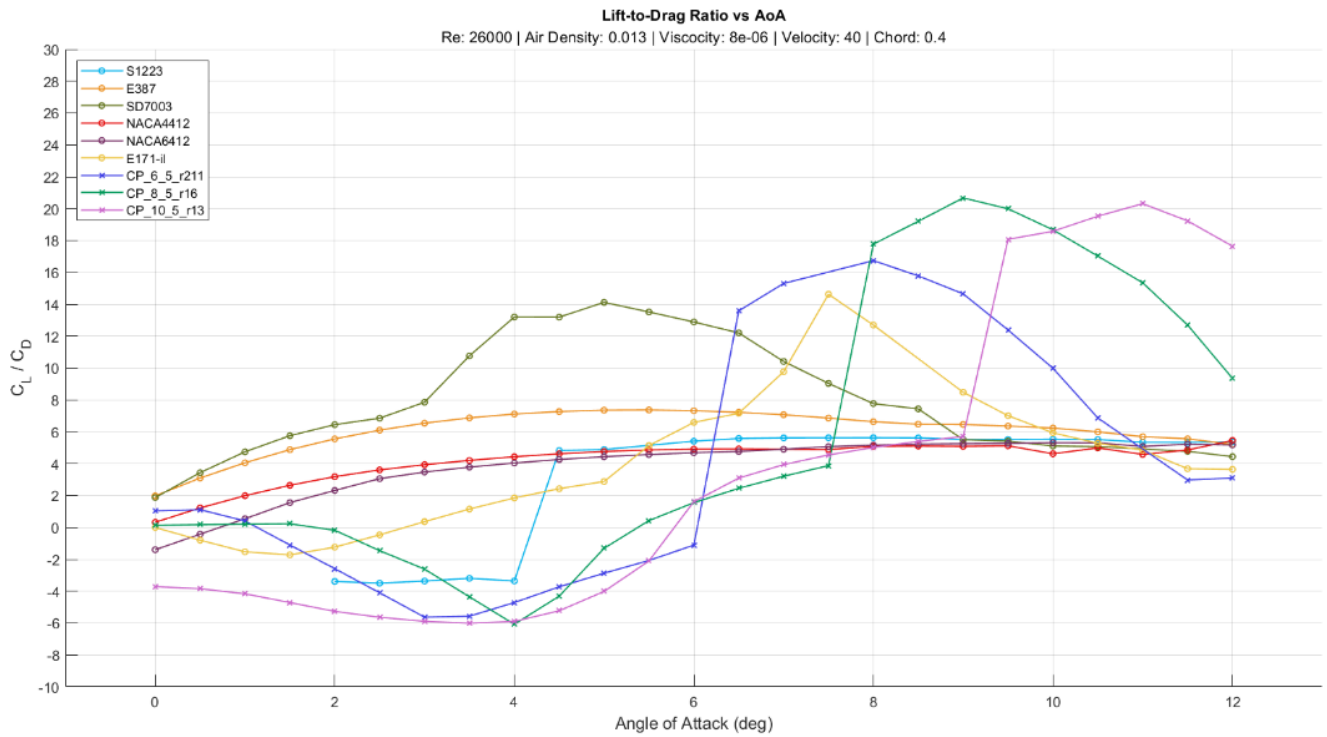


Figure 287: C_L/C_D against AoA in Southern Highlands at Velocity = 40m/s

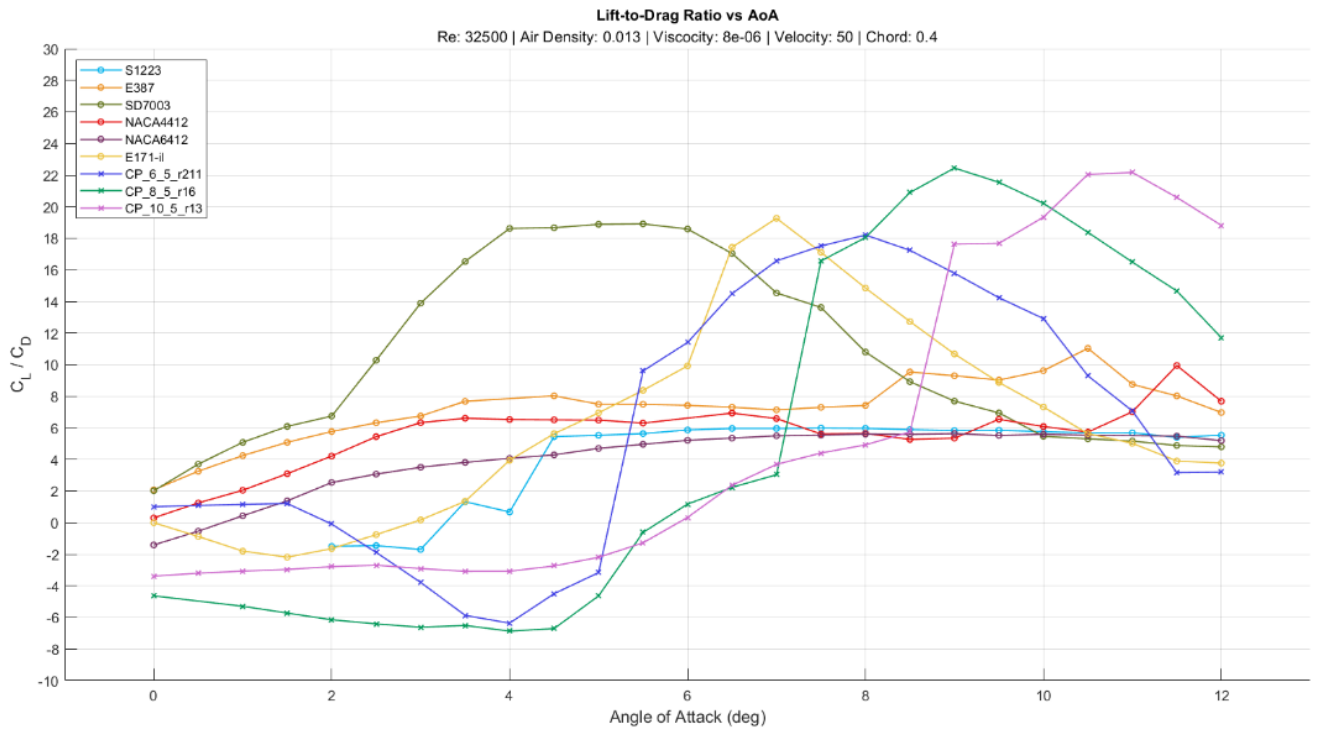


Figure 278: C_L/C_D against AoA in Southern Highlands at Velocity = 50m/s

6.4.4 Further Analysis: Stall Behaviour (CL vs AoA) at High Speeds

Continuing to analyse the stall behaviour of the 9 airfoils at high speeds of $v=40\text{m/s}$ and $v=50\text{m/s}$,

In **Figure 299** and **Figure 30**, the high speed Hellas basin simulations, the S1223 airfoil once again exceeds the capability of all other airfoils in terms of raw coefficient of lift at small AoA; this airfoil, however, exhibits an abrupt stall at 4° for $v=40\text{m/s}$ and 6° for $v=50\text{m/s}$, similar to the stall behaviour of the cambered plates in the southern highlands high-speed simulations (**Figure 31** and **Figure 32**).

In all 4 of the high-speed simulation in the figures below, the S7003 airfoil continues to exhibit very gradual and smooth stalls occurring around 7° - 8° AoA, although in the highest Re number case (**Figure 30** at $\text{Re}=68,800$), the airfoil experience the gradual stall as late as 10° AoA.

The **E171-il** symmetric airfoil and the **E387** airfoil that showed some signs of efficiency at low speeds in chapter **6.4.1**, begin exhibiting good stall behaviour at much larger Re values as seen in the Hellas Basin simulations in **Figure 29** and **Figure 30**.

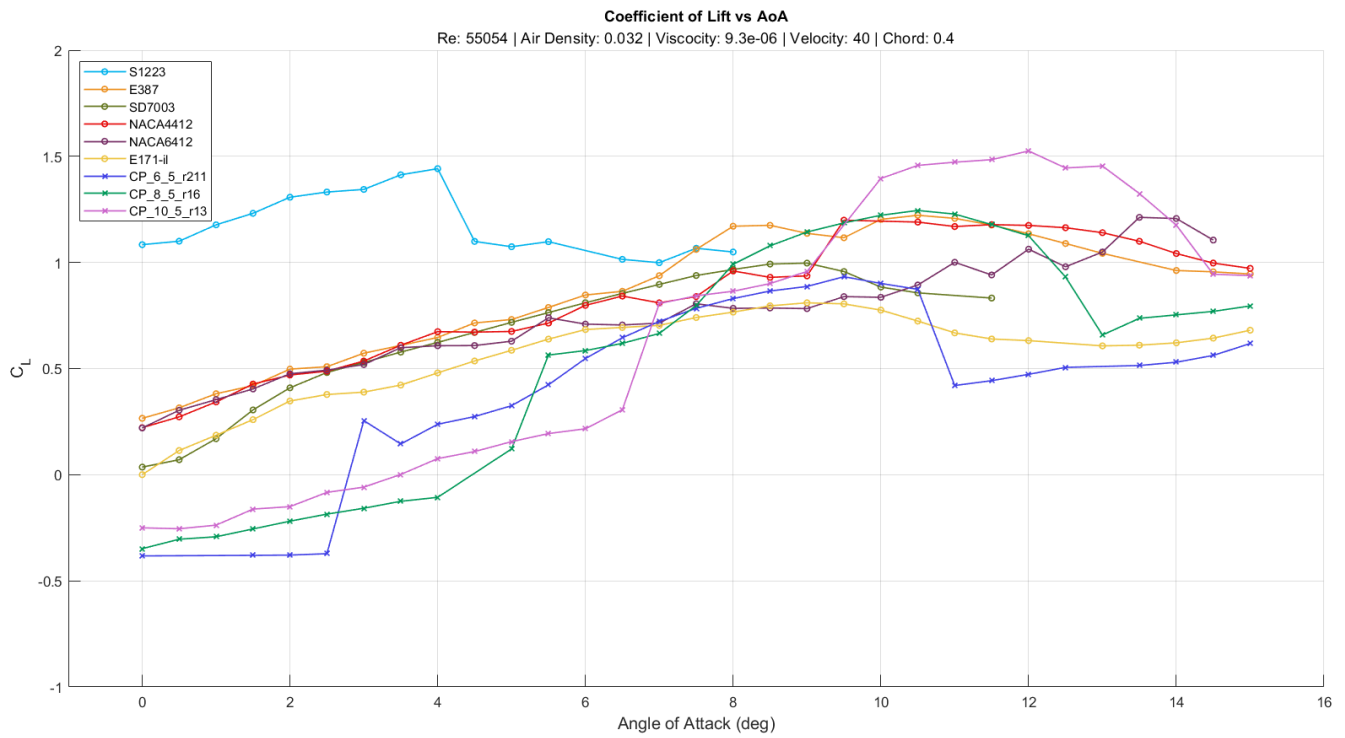


Figure 29: CL against AoA in Hellas basin at Velocity = 40m/s

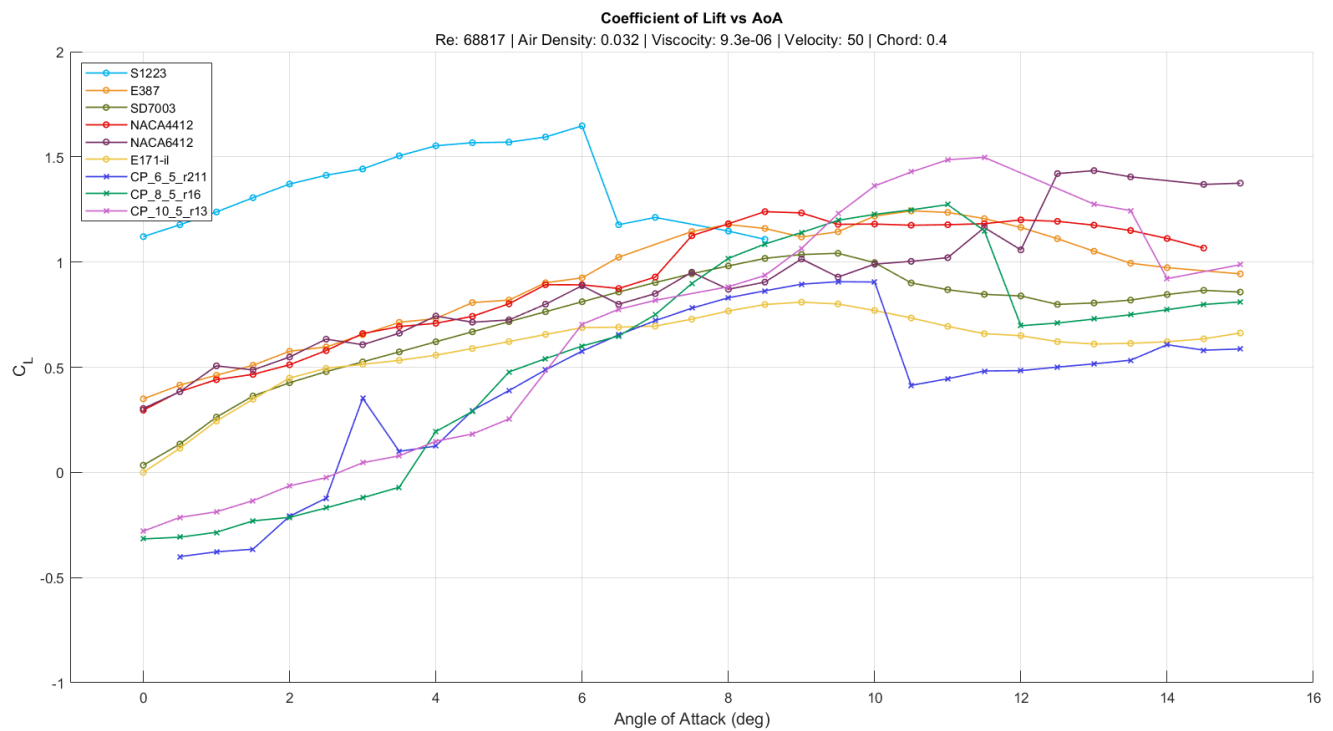


Figure 30: CL against AoA in Hellas basin at Velocity = 50m/s

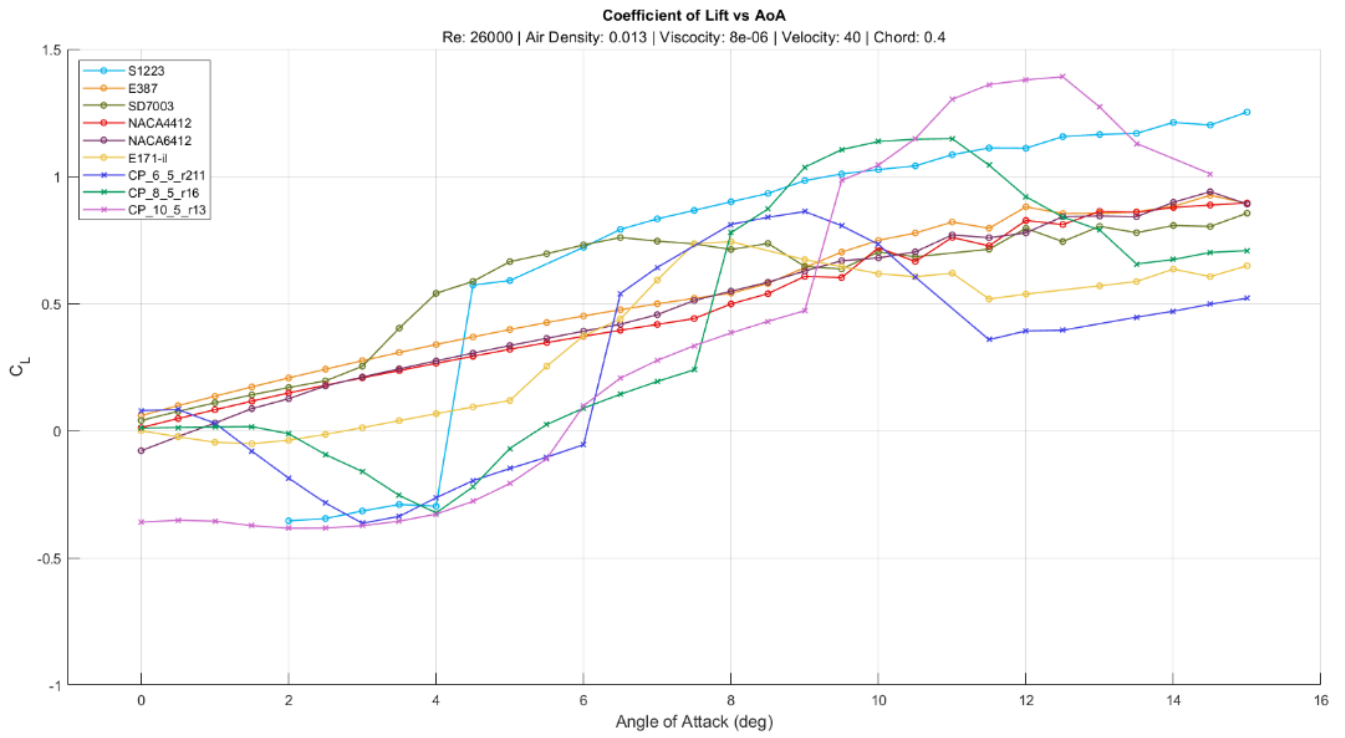


Figure 31: CL against AoA in Southern Highlands at Velocity = 40m/s

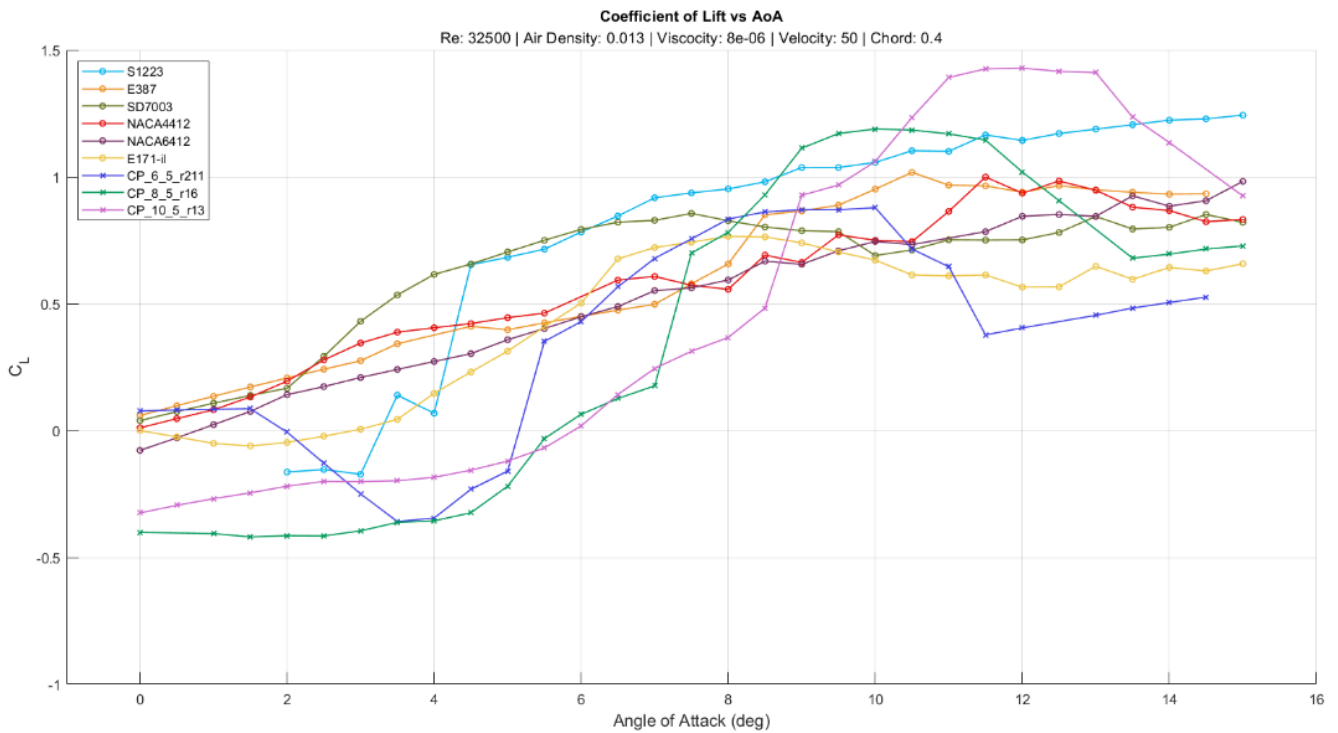


Figure 32: CL against AoA in Southern Highlands at Velocity = 50m/s

6.5 Airfoil Selection Summary

Following the analysis conducted in this chapter, the **SD7003** airfoil shows the most promise in comparison to all other analysed airfoils in terms of gradual stall behaviour, and range of optimal AoA for steady level flight. This airfoil will certainly not meet the requirements of every Martian drone design, however, it can act as a very strong baseline for future airfoil comparison studies, especially when designing larger and more complex vehicles.

The **cambered plates** offer high efficiency over a short range of AoA, with catastrophic stalls occurring shortly after the optimum AoA. This would not result in a good airfoil selection as this vehicle is expected to be able to pitch up and transition into vertical flight, a sudden rapid stall of one wing before the other could cause the vehicle to lose control.

Similarly, the **S1223** airfoil was not selected due to its stall properties, namely that at lower speeds of $v=20\text{m/s}$ and $v=30\text{m/s}$ the airfoil is already considered stalled at 0° AoA, and at higher speeds it experiences a rapid (although not as severe as cambered plates) stall. It does, however, offer a very consistent maximum efficiency at low AoA at very high speeds which could be a viable option should the flight control system and control surfaces be robust enough.

For the purpose of this validation experiment to prove the feasibility of winged flight on Mars, the **S7003** airfoil is a solid solution providing a blend of stall predictability and general efficiency over a large range of conditions. The following chapter will explore the design of the wing using the selected airfoil and further analyse the optimum AoA.

7 Wing Design

It is important that the vehicle can remain stable and in control during the transition phase from a horizontal orientation where the wings are at their optimum AoA, to a vertical orientation where the propellers carry the whole weight of the vehicle and the wings act as nothing more than airbrakes for the horizontal velocity. Additionally, if the wing can operate over a larger AoA range, it increases the vehicle's range of acceptable velocities to maintain level flight as it can pitch up or down by a few degrees.

7.1 Selected Airfoil

Taking the aforementioned requirements into account, the **SD7003** airfoil is the best match providing a stable and more predictable behaviour overall, with substantial lift to drag ratios at multiple tested Reynolds numbers discussed and analysed in **chapter 6: Airfoil Tradeoffs**.

7.1.1 Properties and Characteristics

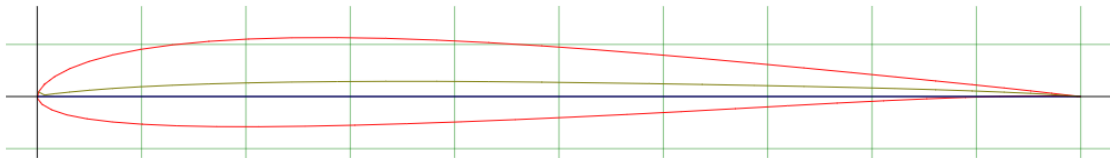


Figure 33: SD7003 airfoil geometry (AirFoil Tools, n.d.)

Airfoil Details:

Selig/Donovan SD7003 low Reynolds number airfoil

Max thickness 8.5% at 24.4% chord.

Max camber 1.2% at 38.3% chord

With a chord length of 0.4m used throughout the airfoil analysis in accordance with requirement **AFR-001**, this would equate to:

Max thickness of 0.034m at 0.0976m from the leading edge

Max camber of 0.0048m at 0.1532m from the leading edge

7.1.2 Materials

The material selected for the wing must be suitable for general space applications, such as low density, temperature resistance and limited/predictable dimension variance with temperature (i.e. the material shouldn't expand in the heat otherwise deployment may be negatively affected). The wings must also be strong enough to withstand **1.5x** the peak load expected to act on it. Using a maximum mass of **10Kg** for the vehicle, and an average Martian gravitational constant of **3.728m/s²**, the maximum weight the wings must be able to support:

$$10kg * 3.728 \frac{m}{s^2} = 37.28 N * 1.5 \approx 56 N$$

A few layers of Carbon Fibre sheets adding up to 1-3mm of thickness would likely be more than sufficient to meet all the aforementioned requirements, while also keeping the thickness of each wing segment to a minimum to aid in mass minimization and easier deployment methods.

7.1.3 Performance in Martian Atmosphere

By generating higher resolution CL vs AoA and CL/CD vs AoA graphs for the SD7003 airfoil at varying Reynolds numbers, a more accurate prediction of the optimum AoA and stall angle for the wing can be made. The Reynolds numbers observed are from 20,000 to 70,000 inclusive, in regular intervals of 10,000. See **Table 6** to compare these Reynolds Values to the calculated low-speed and high-speed values in each of the key identified regions. Note that in order to achieve a Reynolds number of 70,000 in Hellas basin atmospheric conditions (and chord length = 0.4m), the velocity of cruise would need to be approximately 50 m/s.

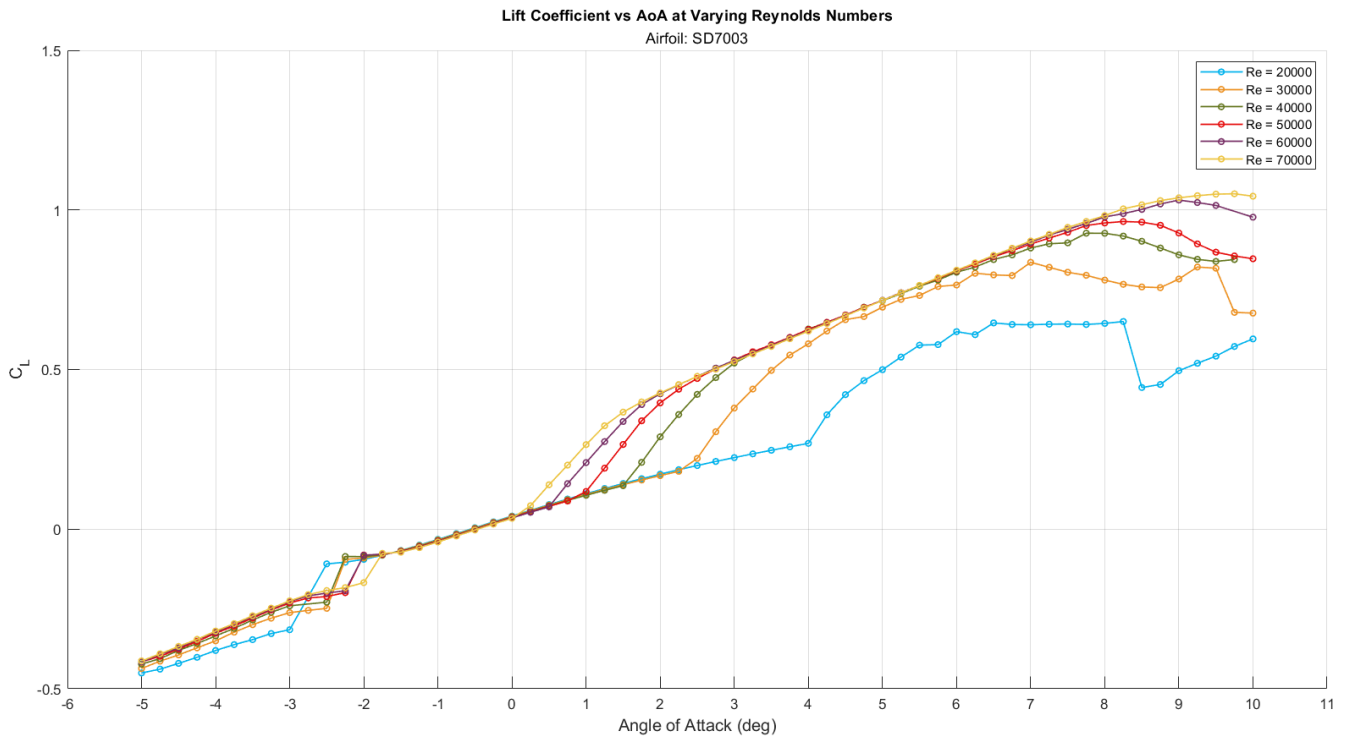


Figure 34: C_L vs AoA of the SD7003 airfoil at regular Reynold number intervals (20k-70k)

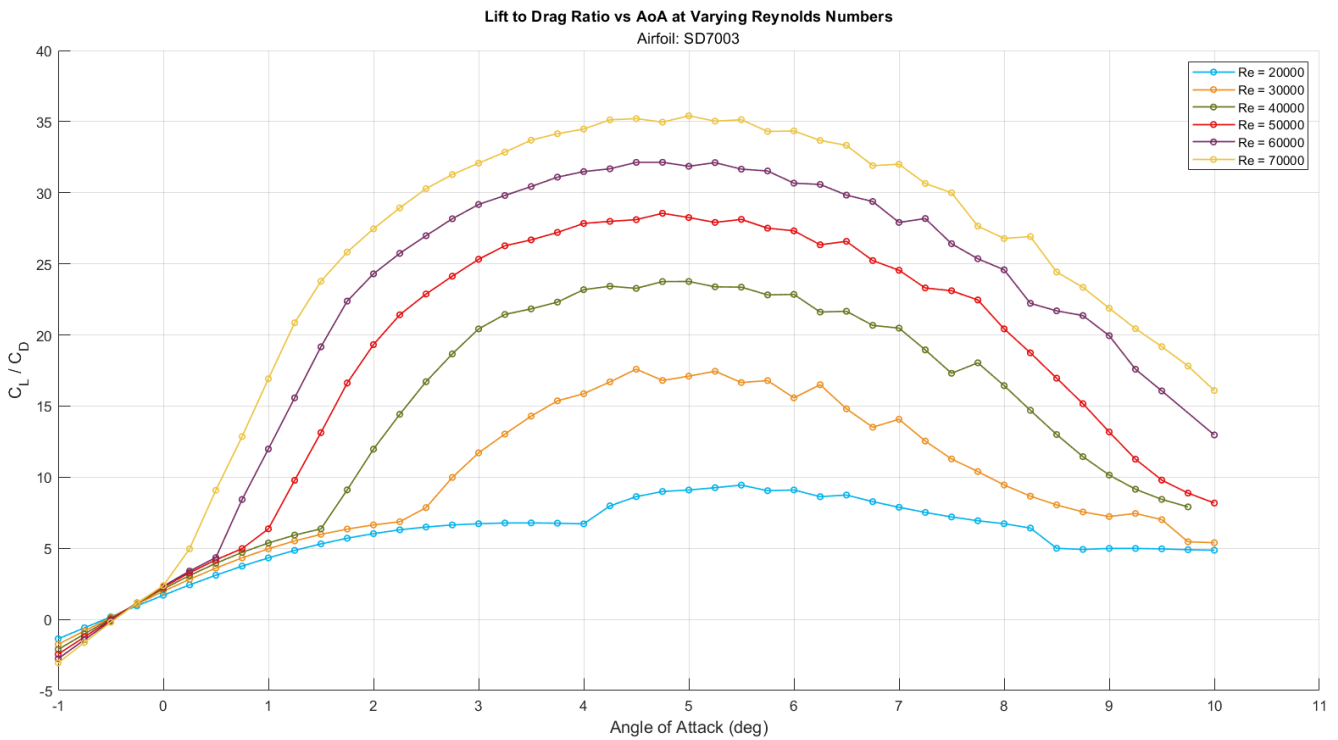


Figure 35: L/D ratio vs AoA of the SD7003 airfoil at regular Reynold number intervals (20k-70k)

The earliest sign of a stall in **Figure 34** (CL vs AoA), is at 7° AoA with a Reynolds number of 30,000. However, at other Reynolds numbers the change to a negative gradient which depicts a stall occurs shortly after 7° AoA with most occurring at 8° AoA or slightly greater.

With the maximum AoA determined at 7°, the optimum alpha angle for cruise should be safely below 7° to ensure accidental stalls don't occur. By observing **Figure 355** it can be seen that the peak aerodynamic efficiency (max lift to drag ratio) systematically occurs around 5° AoA, with the range of 4° to 6° being fairly consistent.

Thus, the operational envelope for the AoA should be 4° to 6° with the airfoils set up for 5° to allow a small margin of pitch adjustment, and not to exceed 7° during flight, with the exception of performing a pitch up manoeuvre to transition from horizontal gliding flight to vertical powered flight for VTOL.

7.2 Deployment Mechanism

The wings deploy using a telescopic tubular mast within the airfoil which locks into place once fully extended. A hot gas reaction could be used to fill the internal volume of the mast, for example by using hypergolic fuels or a solid catalyst like in a space-based reaction control system.

The wing itself would consist of up to 4 segments (requirement **VWR-004**) of decreasing size so they can fit within each other and be deployed telescopically as the internal mast deploys, pulling out each section. Due to the material choice discussed in **7.1.2**, the airfoil can be made extremely thin allowing for minimal airfoil dimension change between segments with any spare material potentially being used as a winglet to limit wing tip overflow ((FAA), 2023). With that being said however, it would be ideal to keep the number of segments to a minimum to not excessively shrink the cross-sectional area of the airfoil in the last wing segment.

7.3 Velocity and Wing Area Variations

Observing **Equation 2: Lift**, it can be seen that surface area of the wing (A) is inversely proportional to the relative velocity (V) of the vehicle to the air. In order to produce enough lift to maintain level flight, it is preferred to increase the velocity as this would result in the vehicle being able to cover a longer range within a single flight, however, it is important to ensure that the payload onboard, especially an optical camera, is able to function properly at those speeds (i.e. not returning blurry images). An additional benefit of increasing velocity as opposed to wing area is that an increase in wing area will add mass and possibly additional complexities with transportation to Mars and/or deployment.

Since vehicle velocity is used to calculate Reynolds number and hence predict CL at a given condition, a simulation can be run at regular intervals of velocity in order to get a more accurate CL for each velocity. These values can then be used in a re-arranged version of the lift equation to determine the surface area required under those conditions to maintain level flight purely from the wings (no vertical acceleration component from the propellers).

Figure 366 below depicts the required wing surface area to maintain level flight with a **5Kg** vehicle at varying velocities, with the respective calculated Reynolds number displayed alongside the velocity in the legend. With a fixed chord length of 0.4m, the wingspan can be approximated as the surface area divided by the chord length; each of the wing's lengths can then be determined as half the wingspan. It can be seen that as the velocity is decreased in regular intervals of 5m/s, the surface area required increases exponentially, so a balance between velocity and wing area must be found. For starters, the optimum AoA determined for the SD7003 airfoil, discussed in **7.1.3**, is at $5^\circ \pm 1^\circ$, therefore the balance must be found within that alpha envelope.

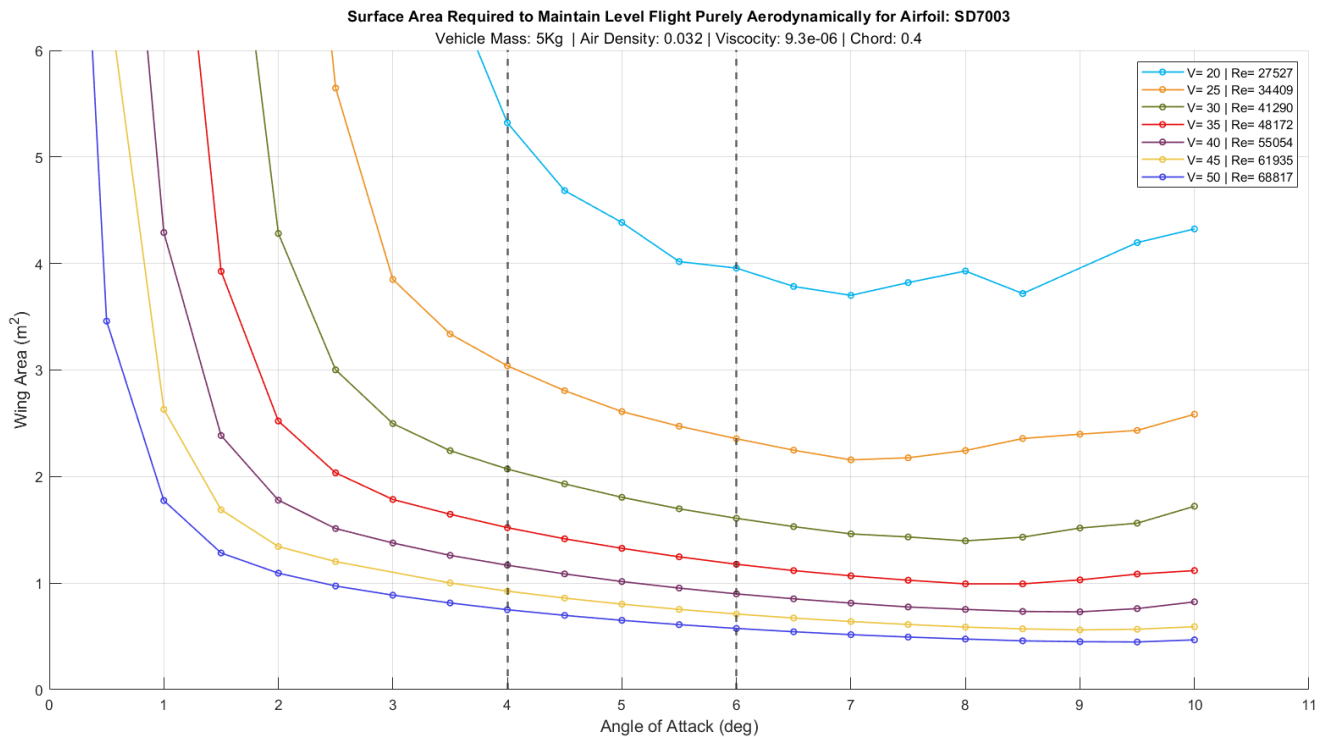


Figure 36: Wing surface area required for a 5Kg vehicle, to maintain level flight in Hellas Basin at varying velocities of cruise

In chapter **6.3: Simulation Conditions**, the airfoil comparison conditions were set at $v=20\text{m/s}$ and $v=30\text{m/s}$; by observing those velocities on **Figure 366**, it can be seen that the wing area required would be approximately 4.4m^2 and 1.9m^2 respectively, which equates to wingspans of 11m and 4.75m . Flight at 20m/s just does not seem reasonable as an individual wing length of 5.5m (half of 11m wingspan) could cause several issues, notably stress on the structure, or stability issues when landing, especially on an uneven surface. A smaller wingspan of 4.75m is more reasonable however could still face similar challenges. The safest option would be to increase the velocity past 30m/s to have smaller wings, as long as the increased velocity doesn't negatively impact the quality of the payload data.

At 40m/s , the Reynolds number is now calculated at $55,054$ and a wing area of only 1m^2 would be required, which would equate to a wingspan of 2.5m , or 2 wings of length 1.25m each which is reasonable.

Figure 377 provides similar data to **Figure 366**, but with a vehicle mass of 10kg. it becomes quickly apparent that an increase in mass somewhat linearly increases the wing surface area required, as for a velocity of 40m/s, instead of 1m^2 , 2m^2 are now needed.

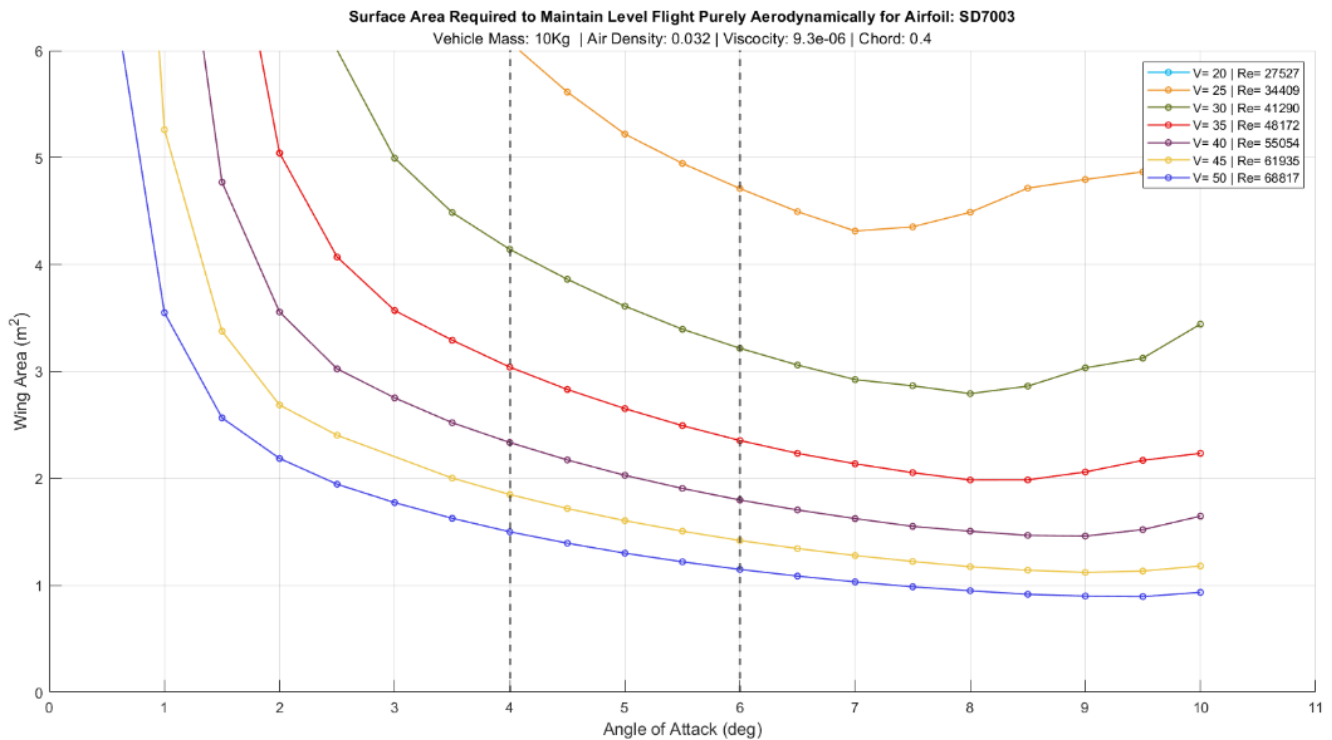


Figure 37: Wing surface area required for a 10Kg vehicle, to maintain level flight in Hellas Basin at varying velocities of cruise

7.4 Wing Design Summary

The **SD7003** airfoil was selected for its stable and predictable behaviour within its optimum (max lift to drag ratio) AoA envelope of 4° to 6° . Additionally, this airfoil tends to experience quite gradual stalls, starting from an AoA of 7° at low speeds (20m/s) which is beneficial for VTOL manoeuvres, and at 9° for higher velocities such as the preferred cruise speed (40m/s to 45m/s). In **Table 8** below, the surface area requirements at key velocities are extracted from **Figure 366**, for the 5kg vehicle, alongside a short analysis:

Table 8: Analysis of wing length requirements at regular intervals of velocity for a 5kg vehicle with 2 wings of chord length 0.4m.

Velocity (m/s)	Area Required (m²)	Single Wing Length (m)	Analysis
20	4.4	5.50	Wing length too long
30	1.9	2.38	Achievable if velocity must be minimised however launch configuration would be noticeably larger and stability affected negatively
35	1.3	1.63	Achievable with 4x 40cm segments. A balance for slower cruise
40	1	1.25	4x 31cm segments for a more compact launch config. A balance between wing area and vehicle velocity
45	0.8	1	3x 33cm segments, ideal wing dimension but velocity better suited for higher altitudes
50	0.7	0.88	Minimal reduction in area for larger velocity, likely too fast for payload use at low altitude

8 Results and Discussion

After analysing the airfoils discussed in **chapter 2.3: Prior work on airfoils for low density atmospheres**, and summarised in chapter **6.2: Shortlist**, some conclusions can be drawn with regards to the airfoil that would be well suited for Mars, and the general feasibility Martian aerial exploration.

8.1 Interpretation of Airfoil Analysis Results

The analysis performed in **chapter 6** has provided some interesting results regarding which airfoil types may be more suited to the Martian atmosphere.

Firstly, the SD7003 airfoil has been thoroughly discussed in this paper, especially in chapter **7.1: Selected Airfoil**. It is a reliable airfoil that offers promising efficiency and stall behaviour data under a variety of conditions, especially at lower speeds which is crucial for the vehicle's ability to transition between horizontal flight and vertical flight for landing manoeuvres. This airfoil is therefore a valid option for the validation experiment, but could function as a baseline for future studies discussed below in **8.3: Future Work**.

In terms of general findings with the airfoils studied, the NACA profile wings which were identical with the exception of a variation in the thickness of the airfoils, revealed that thinner wings perform better in virtually all cases analysed ($Re < 65000$). Similarly, the 3 cambered plates that were studied had identical thickness but varied in camber and radius of curvature; with a smaller camber percentage and larger radius of curvature the results showed that cambered plates work better. Whilst thin cambered plates provided some of the largest L/D ratios of all the studied airfoils, they also tend to exhibit this at very specific angles of attack, and experience drastic and sudden stall effects which can be difficult, but not impossible, to account for in the flight control system.

8.2 Feasibility of Design

With this design being a validation experiment, there are two main feasibility studies to consider. Firstly, whether the validation vehicle itself is feasible and would function in Martian conditions, and secondly, whether making a larger, more functional and capable design would be feasible.

8.2.1 Small 5-10kg Concept

This paper mostly focused on addressing the feasibility question for the test article, a 5-10kg vehicle. It was seen that with a 5kg vehicle it is certainly possible to attain level steady flight with wing lift alone, but the wing area is already quite large compared to the main body of the vehicle, as seen in chapter **7.3: Velocity and Wing Area Variations**.

The ideal conditions for flight that have been determined for a vehicle of mass 5kg would vary on location across the Martian surface, however the preferred location would be Hellas Basin, home to the deepest point on the surface of Mars. Flight in this crater would require a wingspan of approximately 2.5m (2x 1.25m) and flight at $v=40\text{m/s}$. It is worth noting however that velocity and wing area are proportional and flexible as seen in **Table 8: Analysis of wing length requirements at regular intervals of velocity for a 5kg vehicle** with 2 wings of chord length 0.4m.

The vehicle will likely only be able to perform a single flight ever few sols, using the downtime to recharge and collect/transmit data. Useful flight data from this experiment would aid in validating several key aspects of Martian flight including vehicle stability, flight control system reliability and propwash effect on solar panel dust dispersion.

8.2.2 Larger Future Design Concept

The 2 biggest issues at this stage of the feasibility study for a much larger design are the wing area requirements and the power/capability needed of the propeller system to produce enough lift for VTOL.

To compensate for the wing area requirements, more deployable segments and more reliable deployment mechanisms could be introduced, however this increases complexity and risk for airflow instability or dust entry into the vehicle. It would be more realistic to perform an on-site permanent assembly of the main body to the wings or wing segments, whether performed by humans in the not-so-distant future, or robotics prior to human arrival. In theory, a launch vehicle such as SpaceX's Starship with a 9m diameter, could deliver very large wings and the main body of the aerial vehicle for on-site assembly. This would also mean that multiple propellers could be integrated along the wing rather than simply on the main body where the structure is strongest.

It is likely that with an increase in chord length for a design with much bigger wings, the SD7003 airfoil may no longer be the most suited for flight, which would require new research and analysis of airfoils at new calculated Reynolds numbers. An increase in chord length would also result in a rapid increase in lift for a given length of wing, compensating for the added mass.

8.3 Future Work

As with any vehicle design, further work and research can always be implemented to expand the capability, reliability and attractiveness of the vehicle and project. This paper primarily focused on determining a solid foundation for concept, especially with regards to the airfoil and wing dimensions. Notable milestones in the future development of MAEVE include:

- Complete design of the internal sub systems, and selection of hardware, including power supply, propellers, communications and payload.

- Structural analysis of the main body, propeller system and wings with particular focus on the stress the wings will experience throughout flight to minimise material use.
- Further aerodynamic analysis via CFD, wind tunnel and possibly high-altitude Earth tests of finalised design with special consideration of propwash effect on the body and wings.
- Design of a flight control system capable of transitioning between horizontal gliding flight and vertical powered flight, maintaining stability during wing stall.
- Analysis of launch windows that would result in the vehicle reaching Mars shortly after global dust storm season to maximise mission duration, with consideration of existing scheduled launches.

9 Conclusion

This thesis developed and assessed the use of a fixed wing VTOL aircraft to operate in the Martian atmosphere, with particular emphasis on region specific low-Reynolds number airfoil selection and wing sizing. The literature review (Chapter 2) and environmental study (Chapter 3) resulted in the region known as 'Hellas Basin' being the preferred location for this validation experiment due to its significantly increased air density and favourable viscosity which directly contribute to increasing the Reynolds number and therefore the likelihood of airfoil functionality.

The airfoil selected for this study was the SD7003 due to its reliable and predictable behaviour under the range of Re numbers tested between 10,000 and 70,000. This airfoil with a chord length of 0.4m depicted a plateau in CL/CD over an AoA range of 4°-6°, with higher Re conditions increasing the range of the peak efficiency. The airfoil also exhibits a smooth and gradual stall behaviour, around 7°-8°, which is crucial to maintaining stability during a transition between horizontal and vertical flight for VTOL manoeuvres.

A range of velocities were analysed to determine the optimum balance between wing area and velocity to maintain steady level flight, and it was concluded that flight at 35m/s to 40m/s with an individual wing length of 1.6m to 1.25m respectively would be best suited for the validation experiment; each wing would be separated in 4 equal length segments for easier stowage, with the outer most segment containing the control surfaces for in-flight control.

This experiment aims to validate several key features of fixed-wing Martian flight, including an aerodynamic and propulsive flight control system capable of transitioning between horizontal and vertical flight, opening up a pathway to future thin-atmosphere aerial exploration designs for Mars and beyond.

10 References

- (n.d.). Retrieved from AirFoil Tools: <http://airfoiltools.com/index>
- (FAA), F. A. (2023). *Pilot's Handbook of Aeronautical Knowledge*. Retrieved from faa.gov:
https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/faa-h-8083-25c.pdf
- Appelbaum, J., & Flood, D. J. (1989). *Solar Radiation on Mars*. Cleveland, Ohio: NASA Lewis Research Center. Retrieved from
https://www.researchgate.net/publication/256334925_Solar_radiation_on_Mars
- Aprovitola, A., Iuspa, L., Pezzella, G., & Viviani, A. (2024). Flows past airfoils for the low-Reynolds number conditions of flying in Martian atmosphere. *Acta Astronautica*, 221, 94-107. Retrieved from
<https://www.sciencedirect.com/science/article/abs/pii/S0094576524002716>
- Britt, R., Volk, J., Dreim, D., & Applewhite, K. (1999). *Aeroservoelastic Characteristics of the B-2 Bomber and Implications for Future Large Aircraft*. Ottawa: RTO MP-36. Retrieved from
<https://apps.dtic.mil/sti/tr/pdf/ADP010486.pdf>
- Chow, K. C., & Chan, K. L. (n.d.). *PREVAILING DUST STORMS OVER THE HELLAS BASIN ON MARS*. Space Science Institute, Macau University of Science and Technology. Retrieved from https://www-mars.lmd.jussieu.fr/granada2017/abstracts/chow_granada2017.pdf
- Drela, M., & Yourgren, H. (n.d.). Retrieved from XFOIL subsonic airfoil development system:
http://clubmodelisme.free.fr/liens/files/xfoil/xfoil_doc.pdf
- Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M., . . . Huot, J.-P. (n.d.). *Mars Climate Database v6.1: The Web Interface*. Retrieved from https://www-mars.lmd.jussieu.fr/mcd_python/

- Group, U. A. (n.d.). *UIUC Airfoil Coordinates Database*. Retrieved from https://m-selig.ae.illinois.edu/ads/coord_database.html
- Lakdawala, H. N., & Shaikh, A. (2018, April 2). AN AERODYNAMIC PERFORMANCE. *International Journal of Creative Reasearch Thoughts (IJCRT)*, 6, 734. Retrieved from <https://ijcrt.org/papers/IJCRT1812516.pdf>
- Lakdawalla, E. (n.d.). *Map of Mars with major regions labeled*. Retrieved from The Planetary Society: <https://www.planetary.org/space-images/map-mars-major-features>
- NASA. (2021, April 21). *NASA's Ingenuity Mars Helicopter Succeeds in Historic First Flight*. Retrieved from NASA: <https://www.nasa.gov/news-release/nasas-ingenuity-mars-helicopter-succeeds-in-historic-first-flight/>
- NASA. (n.d.). *Dragonfly*. Retrieved from NASA: <https://science.nasa.gov/mission/dragonfly/>
- O'Connor, M. (n.d.). Retrieved from Australian Mathematical Sciences Institute (AMSI): <https://calculate.org.au/wp-content/uploads/sites/15/2018/10/wing-design.pdf>
- Pekar, N. J. (2015, June 29). *Could This Become the First Mars Airplane*. Retrieved from Nasa: <https://www.nasa.gov/aeronautics/could-this-become-the-first-mars-airplane/>
- Sagdeev, R. Z., Linkin, V. M., Blamont, J. E., & Preston, R. A. (1986). The VEGA Venus balloon experiment. Retrieved from <https://ntrs.nasa.gov/citations/19860046078>
- The Planetary Society*. (n.d.). Retrieved from Every Mission to Mars Ever: <https://www.planetary.org/space-missions/every-mars-mission>
- Vuong, T.-H.-N., Nguyen, H.-V., & Le, T.-L. (2025). Numerical study on thin cambered-plate airfoil profiles operating in micro. *Results in Engineering*,

1-14. Retrieved from

<https://www.sciencedirect.com/science/article/pii/S2590123025004451>

Williams, D. D. (2025, May 19). *Mars Fact Sheet*. Retrieved from NSSDCA (NASA's National Space Science Data Center) under NASA Goddard Space Flight Center:

<https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html>

Appendices

Appendix A Ethical approval letter



20 August 2025

Dear Mr Apostolakopoulos ,

Reference: CURES/26332/2025

Project ID: 29806

Title: Design of a Fixed Wing Martian Aerial Vehicle and Low Reynolds Number Airfoil Analysis

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/26332/2025 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B MATLAB Scripts

Five custom built MATLAB scripts were used throughout this paper, summarised in **Table 2: List of MATLAB scripts used**. Appendix B provides all five scripts with a very brief description of how it was used. Please note that all scripts require having both the xfoil executable (xfoil.exe) and the .dat file containing the airfoil geometry data saved in the local directory that the script is saved in.

All the scripts follow the same basic structure:

- Output and Input variables including Re and airfoil selection
- Function that generates input file for xfoil and executes it
- Plotting statements triggered by if statements depending on output variables selected ('PlotTrio' has been used purely for sanity checks and is removed from most scripts, produces a single figure with 3 subplots for CL, CD and CLCD)

The function is the most critical part of the code and will likely be the section to be used in future study using similar methods. It generates a text file with all the required input commands for the xfoil program to execute correctly and then launches xfoil.exe and loads the commands in. xfoil then extracts the data in a polar.txt file and then the function extracts this data into MATLAB arrays for plotting purposes. The following page is dedicated to the function but note that for it to work, the appropriate input variables must be defined in the same MATLAB script.

The lines of text generated in the .txt input file represent separate commands that can be manually inputted in the xfoil command window and if the polar.txt output file is not deleted, an extra prompt must be answered in xfoil (or by adding the corresponding command to the input file) to enable overwriting the previous output file.

Input variables: ***alpha*** and ***Re*** are arrays containing each alpha angle to be simulated, and each Re simulated, but ***iRe*** selects one specific Reynolds number from the Re array. ***airfoilFile*** is a string variable containing the exact name of the geometric .dat file being analysed

```

function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
    % Generating input file
    % run xfoil, Execute Alpha Sweep at specific Re(iRe)
    % Generate AL, CL and CD matrices

    % Delete any existing polar.txt file

    if exist('polar.txt','file'); delete('polar.txt'); end

    % Open a text file to write XFOIL input commands
    fid = fopen('xfoil_input.txt','w');

    fprintf(fid,'LOAD %s\n', airfoilFile);    % load airfoil
    fprintf(fid,'OPER\n');                    % OPER menu
    fprintf(fid,'VISC %.0f\n', Re(iRe));      % viscous Re
    fprintf(fid,'ITER 1000\n');               % max iterations

    % open polar accumulation file / name it polar.txt / press
    'return' again
    fprintf(fid,'PACC\npolar.txt\n\n');

    % AoA input variables (separate comand per AoA)
    for i = 1:length(alpha)
        fprintf(fid,'ALFA %.2f\n', alpha(i));
    end

    fprintf(fid,'PACC\n');                    % close polar file
    fclose(fid);                             % close input txt file

    % Run XFOIL via system call, redirecting commands from file
    system(['xfoil.exe' ' < xfoil_input.txt']);

    % Read the polar results from 'polar.txt'
    data =
    readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
    data = rmmissing(data); % Remove missing values (NaN)
    AL    = data(:,1)';
    CL    = data(:,2)';
    CD    = data(:,3)';

    CLCD  = CL./CD;

end

```

B.1 Airfoil_Analysis_Validation_Copy.m

This script was used to validate the use of xfoil and the associated input files created by the MATLAB script. The script produces results at predetermined Re values for comparison to existing data as well as plotting data at a calculated earth sea level Re to ensure the Re calculations are performed correctly.

```
clc
clear
```

=====

Output Parameters Booleans (1 or 0) =====

```
plotTrio = 0; %3 subplots against alpha (CL, CD, CLCD)
PlotValidation = 1; %fixed dimension graph with interval Re for
validation purposes)
```

=====

Input Parameters ===== Define the airfoil coordinates file (must be added to path)

```
airfoilFile = 'S1223.dat'; % Airfoil coordinate file (S1223 example)

% Angle of attack sweep (degrees)
alpha = (-5:1:15)'; % column vector from -10° to 30°

% Earth atmosphere conditions for validation
rho = 1.225; % air density at sea level [kg/m^3]
mu = 1.789e-5; % air dynamic viscosity [Pa·s] (15°C)
V = 15.0; % flight velocity [m/s]
c = 0.30; % chord length [m] of the wing
Re = [50000 100000 200000 rho*V*c/mu 500000 1000000]; % Reynolds
number (Re = rho*V*c/mu)
iRe = 2; %iteration of renolds number to be run
(Validation will run through all values)
Mach = 0.0; % Mach number (default 0.0 in xfoil)
fprintf('Running XFoil for Re=%.1e, Velocity=%.2f\n', Re, V);
```

```
function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
% =====
% Generating input file
% run xfoil, Execute Alpha Sweep at specific Re(iRe)
% Generate CL and CD matrices
```

```

% =====
% % Initialize arrays to store results
% CL = zeros(size(alpha));
% CD = zeros(size(alpha));
% CLCD = zeros(size(alpha)); % lift-to-drag ratio

if exist('polar.txt','file'); delete('polar.txt'); end %Delete
exissting polar.txt file

% Open a text file to write XFOIL commands
fid = fopen('xfoil_input.txt','w');
fprintf(fid,'LOAD %s\n', airfoilFile); % load airfoil
fprintf(fid,'OPER\n'); % OPER menu
fprintf(fid,'VISC %.0f\n', Re(iRe)); % viscous Re
%fprintf(fid,'VPAR \nN 9\n');
%fprintf(fid,'OPER\n');
fprintf(fid,'ITER 1000\n'); % max iterations
fprintf(fid,'PACC\npolar.txt\n\n'); % open polar
accumulation file / name it polar.txt / press return again
for i = 1:length(alpha)
    fprintf(fid,'ALFA %.2f\n', alpha(i)); % AoA sweep: -5° to
15° in 1° steps
end
fprintf(fid,'PACC\n'); % close polar file
%fprintf(fid,'QUIT\n'); % exit
fclose(fid);

system(['xfoil.exe' ' < xfoil_input.txt']);
% % Run XFOIL via system call, redirecting commands from file
% status = system([xfoilExe ' < xfoil_input.txt']);
% % if status ~= 0
% %     error('XFOIL call failed at alpha=%.2f°', a);
% % end
% STATUS always returns 2 even when useful data produced

% Read the polar results from 'polar.txt'
data =
readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
data = rmmissing(data); % Remove missing values (NaN)
AL = data(:,1)';
CL = data(:,2)';
CD = data(:,3)';

CLCD = CL./CD;
end

```

===== Plot Validation-----

```

if(PlotValidation==1)
    % Generate figure and plot settings
    figure;

    % Axis labels
    xlabel('Angle of Attack (°)','FontSize',12);
    ylabel('C_L / C_D','FontSize',12);
    % Title
    title('Lift-to-Drag Ratio vs AoA');
    % Add legend
    legend('Location','northeast');

    % Axis limits and ticks
    xlim([-10 20]);
    ylim([-20 140]);
    xticks(-10:5:20);
    yticks(-20:20:140);

    grid on;
    hold on

    graphColours = [
        0.00 0.70 0.93;    % Re = 50k
        0.93 0.57 0.13;    % Re = 100k
        0.40 0.47 0.13;    % Re = 200k
        0.90 0.05 0.05;    % Custom Re
        0.47 0.19 0.40;    % Re = 500k
        0.93 0.77 0.25;    % Re = 1M
    ];

    for iRe = 1:length(Re) %iteration of Renoylds number
        % Run function once to generate data
        [AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);

        legendStr= sprintf('Re = %.0f', Re(iRe));

        plot(AL, CLCD, '-o',...
            'color', graphColours(iRe,:),...
            'LineWidth', 1,...
            'DisplayName', legendStr);

    end
end

```

B.2 Airfoil_Analysis_ Comparisson_Plots.m

This script is an adaptation of the validation copy (B.1) that plots CL/CD / AoA data at any given Reynolds number (pre-determined or locally calculated) for a range of airfoils stated at the beginning, where the corresponding .dat files must be in the working directory.

```
clc
clear
```

=====

Output Parameters Booleans (1 or 0) =====

```
plotTrio = 0; %3 subplots against alpha (CL, CD, CLCD)
PlotMultiComp = 1; %fixed dimension graph with interval Re for
validation purposes)
```

=====

Input Parameters ===== Define the airfoil coordinates file (must be added to path)

```
airfoilFileList =
["S1223.dat";"E387.dat";"SD7003.dat";"NACA4412.dat";"NACA6412.dat";"E171-
il.dat";"CP_6_5_r211.dat";"CP_8_5_r16.dat";"CP_10_5_r13.dat"];
airfoilFile      = airfoilFileList(7); % Select airfoil file to be used
in this run

alpha = (0:0.5:12)'; % Angle of attack sweep (degrees)
0:0.5:12
gMars = 3.728; % [m/s^2] Mars gravitational constant average
Mach = 0.0; % Mach number (default 0.0 in xfoil)

% Reynolds number (Re = rho*V*c/mu)
rho = 3.2e-2; % [kg/m^3] Average air density in Hellas
Basin 3.2e-2
mu = 9.3e-6; % [Pa.s] Average air dynamic viscosity in
Hellas Basin 9.3e-6
V = 40.0; % [m/s] Reletive air velocity
c = 0.40; % [m] Chord length of the airfoil

Re = round(rho*V*c/mu,0); % OR SELECT REYNOLDS NUMBER USING iRe
(set iRe at 1 to use calculation)
%Re = [7.27e3 1.09e4 18519 21573];
```

```
iRe = 1; %iteration of renolds number to be run
(Validation will run through all values regardless)
```

```
%fprintf('Running XFOIL for Re=%.1e, Velocity=%.2f\n', Re, V);
```

```
function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
% =====
% Generating input file
% run xfoil, Execute Alpha Sweep at specific Re(iRe)
% Generate CL and CD matricies
% =====
% % Initialize arrays to store results
% CL = zeros(size(alpha));
% CD = zeros(size(alpha));
% CLCD = zeros(size(alpha)); % lift-to-drag ratio

if exist('polar.txt','file'); delete('polar.txt'); end %Delete
exisisting polar.txt file

% Open a text file to write XFOIL commands
fid = fopen('xfoil_input.txt','w');
fprintf(fid,'LOAD %s\n', airfoilFile); % load airfoil
fprintf(fid,'OPER\n'); % OPER menu
fprintf(fid,'VISC %.0f\n', Re(iRe)); % viscous Re
%fprintf(fid,'VPAR \nN 9\n');
%fprintf(fid,'OPER\n');
fprintf(fid,'ITER 1000\n'); % allowed max
iterations
fprintf(fid,'PACC\npolar.txt\n\n'); % open polar
accumulation file / name it polar.txt / press return again
for i = 1:length(alpha)
% if (strcmp(airfoilFile,"S1223.dat")==1 && i<5)
% % If S1223.dat and early alpha iteration (0-2 deg),
skip
% else
fprintf(fid,'ALFA %.2f\n', alpha(i)); % AoA sweep:
according to input defined
% end
end
fprintf(fid,'PACC\n'); % close polar file
fclose(fid);

system(['xfoil.exe' ' < xfoil_input.txt']);
% % Run XFOIL via system call, redirecting commands from file
```

```

        % status = system([xfoilExe ' < xfoil_input.txt']);
        % % if status ~= 0
        % %     error('XFOIL call failed at alpha=%.2f°', a);
        % % end
        % STATUS always returns 2 even when useful data produced

        % Read the polar results from 'polar.txt'
        data =
readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
        data = rmmissing(data); % Remove missing values (NaN)
        AL    = data(:,1)';
        CL    = data(:,2)';
        CD    = data(:,3)';

        CLCD  = CL./CD;

end

```

===== Plot CL/CD

```

if(PlotMultiComp==1)
    % Generate figure and plot settings
    figure;

    % Axis labels
    xlabel('Angle of Attack (deg)','FontSize',12);
    ylabel('C_L / C_D','FontSize',12);
    % Title
    subTitleText = append( 'Re: ', string(Re(iRe)), ' | Air Density: ',
string(rho), ' | Viscosity: ', string(mu),...
        ' | Velocity: ', string(V), ' | Chord: ',
string(c) );
    title('Lift-to-Drag Ratio vs AoA',subTitleText);
    % Add legend
    legend('Location','northwest','Interpreter','none');

    % Axis limits and ticks
    xlim([-1 13]);
    ylim([-10 50]); % Changed from 30 to 50 for High speed Hellas
Basin
    xticks(-20:2:20);
    yticks(-10:2:60);

    grid on;
    hold on

    graphColours = [
0.00 0.70 0.93; % S 1223

```

```

0.93 0.57 0.13; % E 387
0.40 0.47 0.13; % SD 7003
0.90 0.05 0.05; % NACA 4412
0.47 0.19 0.40; % NACA 6412
0.93 0.77 0.25; % E171-il
0.25 0.25 0.90; % CP_6_5_r211
0.00 0.60 0.35; % CP_8_5_r16
0.80 0.40 0.80; % CP_10_5_r13
];

for iFoil = 1:length(airfoilFileList) %iteration of Renoylds number
    % Run function once to generate data
    airfoilFile = airfoilFileList(iFoil,:);
    [AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);

    legendStr= sprintf(erase(airfoilFile, '.dat'));

    if strncmp(airfoilFile, 'CP_',3)
        plot(AL, CLCD, '-x', 'MarkerSize',5,...
            'color', graphColours(iFoil,:),...
            'LineWidth', 1,...
            'DisplayName', string(legendStr));
    else
        plot(AL, CLCD, '-o', 'MarkerSize',4,...
            'color', graphColours(iFoil,:),...
            'LineWidth', 1,...
            'DisplayName', legendStr);
    end
end
end
end

```

B.3 Airfoil_Analysis_ Comparisson_Plots _CL_Stall.m

This script is a slight adaptation of the previous CL/CD script (B.2) used to plot the CL / AoA data for the same airfoils at the same Re conditions.

```
clc
clear
```

Output Parameters Booleans (1 or 0) =====

```
plotTrio = 0; %3 subplots against alpha (CL, CD, CLCD)
PlotMultiComp = 1; %fixed dimension graph with interval Re for
validation purposes)
```

=====

Input Parameters ===== Define the airfoil coordinates file (must be added to path)

```
airfoilFileList =
["S1223.dat"; "E387.dat"; "SD7003.dat"; "NACA4412.dat"; "NACA6412.dat"; "E171-
il.dat"; "CP_6_5_r211.dat"; "CP_8_5_r16.dat"; "CP_10_5_r13.dat"];
airfoilFile      = airfoilFileList(1); % Select airfoil file to be used
in this run

alpha = (0:0.5:15)'; % Angle of attack sweep (degrees)
0:0.5:12
gMars = 3.728; % [m/s^2] Mars gravitational constant average
Mach = 0.0; % Mach number (default 0.0 in xfoil)

% Reynolds number (Re = rho*V*c/mu)
rho = 3.2e-2; % [kg/m^3] Average air density in Hellas
Basin 3.2e-2 | 1.3e-2
mu = 9.3e-6; % [Pa·s] Average air dynamic viscosity in
Hellas Basin 9.3e-6 | 8.0e-6
V = 40.0; % [m/s] Reletive air velocity
c = 0.40; % [m] Chord length of the airfoil

Re = round(rho*V*c/mu,0); % OR SELECT REYNOLDS NUMBER USING iRe
(set iRe at 1 to use calculation)
%Re = [7.27e3 1.09e4 18519 21573];
iRe = 1; %iteration of renolds number to be run
(Validation will run through all values regardless)

%fprintf('Running XF0IL for Re=%.1e, Velocity=%.2f\n', Re, V);
```

```

-----
function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
    % =====
    % Generating input file
    % run xfoil, Execute Alpha Sweep at specific Re(iRe)
    % Generate CL and CD matrices
    % =====
    % % Initialize arrays to store results
    % CL = zeros(size(alpha));
    % CD = zeros(size(alpha));
    % CLCD = zeros(size(alpha)); % lift-to-drag ratio

    if exist('polar.txt','file'); delete('polar.txt'); end %Delete
    exissting polar.txt file

    % Open a text file to write XFOIL commands
    fid = fopen('xfoil_input.txt','w');
    fprintf(fid,'LOAD %s\n', airfoilFile); % load airfoil
    fprintf(fid,'OPER\n'); % OPER menu
    fprintf(fid,'VISC %.0f\n', Re(iRe)); % viscous Re
    %fprintf(fid,'VPAR \nN 9\n');
    %fprintf(fid,'OPER\n');
    fprintf(fid,'ITER 1000\n'); % allowed max
iterations
    fprintf(fid,'PACC\npolar.txt\n\n'); % open polar
accumulation file / name it polar.txt / press return again
    for i = 1:length(alpha)
        % if (strcmp(airfoilFile,"S1223.dat")==1 && i<5)
        % % If S1223.dat and early alpha iteration (0-2 deg),
skip
        % else
        fprintf(fid,'ALFA %.2f\n', alpha(i)); % AoA sweep:
according to input defined
        % end
    end
    fprintf(fid,'PACC\n'); % close polar file
    fclose(fid);

    system(['xfoil.exe' ' < xfoil_input.txt']);
    % % Run XFOIL via system call, redirecting commands from file
    % status = system([xfoilExe ' < xfoil_input.txt']);
    % % if status ~= 0
    % % error('XFOIL call failed at alpha=%.2f°', a);
    % % end
    % STATUS always returns 2 even when useful data produced

```

```

        % Read the polar results from 'polar.txt'
        data =
readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
        data = rmmissing(data); % Remove missing values (NaN)
        AL    = data(:,1)';
        CL    = data(:,2)';
        CD    = data(:,3)';

        CLCD  = CL./CD;

end

```

===== Plot CL

```

if(PlotMultiComp==1)
    % Generate figure and plot settings
    figure;

    % Axis labels
    xlabel('Angle of Attack (deg)','FontSize',12);
    ylabel('C_L','FontSize',12);
    % Title
    subTitleText = append( 'Re: ', string(Re(iRe)), ' | Air Density: ',
string(rho), ' | Viscosity: ', string(mu),...
        ' | Velocity: ', string(V), ' | Chord: ',
string(c) );
    title('Coefficient of Lift vs AoA',subTitleText);
    % Add legend
    legend('Location','northwest','Interpreter','none');

    % Axis limits and ticks
    xlim([-1 16]);
    ylim([-1 2]);
    xticks(-20:2:20);
    yticks(-10:0.5:30);

    grid on;
    hold on

    graphColours = [
0.00 0.70 0.93;    % S 1223
0.93 0.57 0.13;    % E 387
0.40 0.47 0.13;    % SD 7003
0.90 0.05 0.05;    % NACA 4412
0.47 0.19 0.40;    % NACA 6412
0.93 0.77 0.25;    % E171-il
0.25 0.25 0.90;    % CP_6_5_r211

```

```

0.00 0.60 0.35;    % CP_8_5_r16
0.80 0.40 0.80;    % CP_10_5_r13
];

for iFoil = 1:length(airfoilFileList) %iteration of Renoylds number
    % Run function once to generate data
    airfoilFile = airfoilFileList(iFoil,:);
    [AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);

    legendStr= sprintf(erase(airfoilFile, '.dat'));

    if strncmp(airfoilFile,'CP_',3)
        plot(AL, CL, '-x', 'MarkerSize',5,...
            'color', graphColours(iFoil,:),...
            'LineWidth', 1,...
            'DisplayName', string(legendStr));
    else
        plot(AL, CL, '-o', 'MarkerSize',4,...
            'color', graphColours(iFoil,:),...
            'LineWidth', 1,...
            'DisplayName', legendStr);
    end

end

end
end

```

B.4 Airfoil_Analysis_ Comparisson_Plots _CL_SD7003.m

This script is a combination of the CL/CD and CL scripts (B.2 and B.3) used to plot CL/CD / AoA and CL / AoA data for a specific airfoil (set to the SD7003 airfoil) at a range of Reynolds numbers that are calculated based off of input velocities. The data is also generated and plotted at a higher resolution to perform a more in-depth analysis of the specific airfoil selected for chapter 7.

```
clc
clear
```

=====

Output Parameters Booleans (1 or 0) =====

```
plotTrio = 0; %3 subplots against alpha (CL, CD, CLCD)
PlotCLComp = 1; %fixed dimension graph with interval Re for validation
purposes)
```

=====

Input Parameters ===== Define the airfoil coordinates file (must be added to path)

```
airfoilFile = 'SD7003.dat'; % Airfoil coordinate file (S1223 example)

% Angle of attack sweep (degrees)
alpha = (-5:0.25:10)'; % column vector from -10° to 30°

% Earth atmosphere conditions for validation
rho = 1.225; % air density at sea level [kg/m^3]
mu = 1.789e-5; % air dynamic viscosity [Pa·s] (15°C)
V = 15.0; % flight velocity [m/s]
c = 0.30; % chord length [m] of the wing
Re = [20000 30000 40000 50000 60000 70000]; % Reynolds number (Re = rho*V*c/mu)
iRe = 2; %iteration of renolds number to be run
(Validation will run through all values)
Mach = 0.0; % Mach number (default 0.0 in xfoil)
fprintf('Running XFOIL for Re=%.1e, Velocity=%.2f\n', Re, V);
```

```
function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
% =====
```

```

% Generating input file
% run xfoil, Execute Alpha Sweep at specific Re(iRe)
% Generate CL and CD matrices
% =====
% % Initialize arrays to store results
% CL = zeros(size(alpha));
% CD = zeros(size(alpha));
% CLCD = zeros(size(alpha)); % lift-to-drag ratio

if exist('polar.txt','file'); delete('polar.txt'); end %Delete
exissting polar.txt file

% Open a text file to write XFOIL commands
fid = fopen('xfoil_input.txt','w');
fprintf(fid,'LOAD %s\n', airfoilFile); % load airfoil
fprintf(fid,'OPER\n'); % OPER menu
fprintf(fid,'VISC %.0f\n', Re(iRe)); % viscous Re
%fprintf(fid,'VPAR \nN 9\n');
%fprintf(fid,'OPER\n');
fprintf(fid,'ITER 1000\n'); % max iterations
fprintf(fid,'PACC\npolar.txt\n\n'); % open polar
accumulation file / name it polar.txt / press return again
for i = 1:length(alpha)
    fprintf(fid,'ALFA %.2f\n', alpha(i)); % AoA sweep: -5° to
15° in 1° steps
end
fprintf(fid,'PACC\n'); % close polar file
%fprintf(fid,'QUIT\n'); % exit
fclose(fid);

system(['xfoil.exe' ' < xfoil_input.txt']);
% % Run XFOIL via system call, redirecting commands from file
% status = system([xfoilExe ' < xfoil_input.txt']);
% % if status ~= 0
% %     error('XFOIL call failed at alpha=%.2f°', a);
% % end
% STATUS always returns 2 even when useful data produced

% Read the polar results from 'polar.txt'
data =
readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
data = rmmissing(data); % Remove missing values (NaN)
AL = data(:,1)';
CL = data(:,2)';
CD = data(:,3)';

```

```

        CLCD = CL./CD;
end

```

=====Fig 1 CL

```

if(PlotCLComp==1)
    % Generate figure and plot settings
    figure;
    hold on

    % Axis labels
    xlabel('Angle of Attack (deg)','FontSize',12);
    ylabel('C_L','FontSize',12);
    % Title
    title('Lift Coefficient vs AoA at Varying Reynolds
Numbers','Airfoil: SD7003');
    % Add legend
    legend('Location','northeast');

    % Axis limits and ticks
    xlim([-6 11]);
    ylim([-0.5 1.5]);
    xticks(-10:1:20);
    yticks(-0.5:0.5:1.5);

    grid on;

    graphColours = [
    0.00 0.70 0.93;    % Re = 20k
    0.93 0.57 0.13;    % Re = 30k
    0.40 0.47 0.13;    % Re = 40k
    0.90 0.05 0.05;    % Re = 50k
    0.47 0.19 0.40;    % Re = 60k
    0.93 0.77 0.25;    % Re = 70k
    ];

    for iRe = 1:length(Re) %iteration of Renoylds number
        % Run function once to generate data
        [AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);

        legendStr= sprintf('Re = %.0f', Re(iRe));

        plot(AL, CL, '-o', 'MarkerSize',4,...
            'color', graphColours(iRe,:),...
            'LineWidth', 1,...
            'DisplayName', legendStr);
    end
end

```

```

end
hold off

```

=====Fig 1 CL/CD

```

figure;
hold on

% Axis labels
xlabel('Angle of Attack (deg)', 'FontSize', 12);
ylabel('C_L / C_D', 'FontSize', 12);
% Title
title('Lift to Drag Ratio vs AoA at Varying Reynolds
Numbers', 'Airfoil: SD7003');
% Add legend
legend('Location', 'northeast');

% Axis limits and ticks
xlim([-1 11]);
ylim([-5 40]);
xticks(-1:1:20);
yticks(-5:5:50);

grid on;

graphColours = [
0.00 0.70 0.93; % Re = 20k
0.93 0.57 0.13; % Re = 30k
0.40 0.47 0.13; % Re = 40k
0.90 0.05 0.05; % Re = 50k
0.47 0.19 0.40; % Re = 60k
0.93 0.77 0.25; % Re = 70k
];

for iRe = 1:length(Re) %iteration of Renoylds number
% Run function once to generate data
[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);

legendStr= sprintf('Re = %.0f', Re(iRe));

plot(AL, CLCD, '-o', 'MarkerSize', 4, ...
'color', graphColours(iRe,:), ...
'LineWidth', 1, ...

```

```
        'DisplayName', legendStr);  
    end  
end
```

B.5 Airfoil_Analysis.m

The final script is an adaptation of the case specific script (B.4) which calculated wing area requirements to generate the exact lift required to match the weight of the vehicle (5kg or 10kg) in Martian gravity. This determines the amount of wing area required to maintain level flight at varying velocities to aid in determining optimum area to velocity ratio. Additionally, vertical black lines have been added to depict this specific airfoil's optimum AoA as determined by analysing script B.4 above.

```
clc
clear
```

Output Parameters Booleans (1 or 0) =====

```
plotAreaFinder = 1; %
```

Input Parameters ===== Define the airfoil coordinates file (must be added to path)

```
airfoilFileList =
["S1223.dat"; "E387.dat"; "SD7003.dat"; "NACA4412.dat"; "NACA6412.dat"; "E171-
il.dat"; "CP_6_5_r211.dat"; "CP_8_5_r16.dat"; "CP_10_5_r13.dat"];
airfoilFile      = airfoilFileList(3); % Select airfoil file to be used
in this run

alpha = (0:0.5:10)'; % Angle of attack sweep (degrees)
gMars = 3.728;        % [m/s^2] Mars gravitational constant average
m = 10;               % [Kg] total mass of probe
Mach = 0.0;           % Mach number (default 0.0 in xfoil)

% Reynolds number (Re = rho*V*c/mu)
rho = 3.2e-2;         % [kg/m^3] Average air density in Hellas
Basin 3.2e-2
mu = 9.3e-6;          % [Pa.s] Average air dynamic viscosity in
Hellas Basin 9.3e-6
V = [20 25 30 35 40 45 50]; % [m/s] Relative air velocity
c = 0.40;             % [m] Chord length of the airfoil

%Re = rho*V*c/mu;     % OR SELECT REYNOLDS NUMBER USING iRe (set
iRe at 1 to use calculation)
Re = [5455 8500 9750 18519 21573];
iRe = 1;              %iteration of renolds number to be run
(Validation will run through all values regardless)
```

```

iV = 1;                                %iteration of velocity

Lsteady = m*gMars; % Lift required to maintain steady altitude = mass *
Martian gravitational constant

%fprintf('Running XFOIL for Re=%.1e, Velocity=%.2f\n', Re, V);

```

```

-----

function[AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe)
    % =====
    % Generating input file
    % run xfoil, Execute Alpha Sweep at specific Re(iRe)
    % Generate CL and CD matrices
    % =====
    % % Initialize arrays to store results
    % CL = zeros(size(alpha));
    % CD = zeros(size(alpha));
    % CLCD = zeros(size(alpha)); % lift-to-drag ratio

    if exist('polar.txt','file'); delete('polar.txt'); end %Delete
    exissting polar.txt file

    % Open a text file to write XFOIL commands
    fid = fopen('xfoil_input.txt','w');
    fprintf(fid,'LOAD %s\n', airfoilFile); % load airfoil
    fprintf(fid,'OPER\n'); % OPER menu
    fprintf(fid,'VISC %.0f\n', Re(iRe)); % viscous Re
    %fprintf(fid,'VPAR \nN 9\n');
    %fprintf(fid,'OPER\n');
    fprintf(fid,'ITER 1000\n'); % allowed max
iterations
    fprintf(fid,'PACC\npolar.txt\n\n'); % open polar
accumulation file / name it polar.txt / press return again
    for i = 1:length(alpha)
        fprintf(fid,'ALFA %.2f\n', alpha(i)); % AoA sweep:
according to input defined
    end
    fprintf(fid,'PACC\n'); % close polar file
    fclose(fid);

    system(['xfoil.exe' ' < xfoil_input.txt']);
    % % Run XFOIL via system call, redirecting commands from file
    % status = system([xfoilExe ' < xfoil_input.txt']);
    % % if status ~= 0
    % %     error('XFOIL call failed at alpha=%.2f°', a);

```

```

        % % end
        % STATUS always returns 2 even when useful data produced

        % Read the polar results from 'polar.txt'
        data =
readmatrix('polar.txt','FileType','text','NumHeaderLines',12);
        data = rmmissing(data); % Remove missing values (NaN)
        AL    = data(:,1)';
        CL    = data(:,2)';
        CD    = data(:,3)';

        CLCD  = CL./CD;
end

```

===== Area finder plots

```

if (plotAreaFinder==1)

    %L = (CL*rho*V*V*A)/2;
    %D = (CD*rho*V*V*A)/2;

    % Generate figure
    figArea = figure('Name','Surface Area Required');

    xlabel('Angle of Attack (deg)','FontSize',12);
    ylabel('Wing Area (m^2)','FontSize',12);

    % Title
    subTitleText = append( 'Vehicle Mass: ', string(m),'Kg | Air
Density: ', string(rho),' | Viscosity: ', string(mu),...
                           ' | Chord: ', string(c) );
    title(append('Surface Area Required to Maintain Level Flight Purely
Aerodynamically for Airfoil: ', erase(airfoilFile, '.dat')),
subTitleText, 'Interpreter','none');

    % Add legend
    legend('Location','northeast');

    % Axis limits and ticks
    xlim([0 11]);
    ylim([0 6]);
    xticks(0:1:16);
    yticks(0:1:10);

    grid on;
    hold on

```

```

graphColours = [
0.00 0.70 0.93; % Velocity 1
0.93 0.57 0.13; %
0.40 0.47 0.13; %
0.90 0.05 0.05; %
0.47 0.19 0.40; %
0.93 0.77 0.25; %
0.25 0.25 0.90; %
0.00 0.60 0.35; %
0.80 0.40 0.80; %
];

for iV=1:length(V)

    % Run function once to generate data at specified velocity
    Re = round((rho*V(iV)*c)/mu,0);
    [AL, CL, CD, CLCD] = alphaSweep(alpha,airfoilFile,Re,iRe);
    Area= zeros(1,length(CL)); % reset/initialize area matrix

    for iArea=1:length(CL)
        % Rearrange lift equation to find area required for Lsteady
        at specified velocity
        Area(iArea) = (2*Lsteady) / (CL(iArea)*rho*V(iV)^2);
    end

    % Find what index Alpha = 0 is
    [idxRow,idxCol] = find(AL==0);

    % plot only data after Alpha=0 (nonsensicle data before)
    plot(AL(1, idxCol:end), Area(1, idxCol:end),'-o',
'MarkerSize',4,...
        'color', graphColours(iV,:),...
        'LineWidth', 1,...
        'DisplayName', append('V= ',string(V(iV)),' | Re= ',
string(Re(iRe))));

    end
    xline(4,"--v",'HandleVisibility','off','LineWidth',1.5) % plot x=4
and x=6 dotted balck line to depict rough optimum ...
    xline(6,"--v",'HandleVisibility','off','LineWidth',1.5)% ...region
of operation for SD7003 airfoil as determined by CL plots

end %if statement

```