The Atmosphere

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January 22, 2004

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0 Introduction

1 Introduction

This is an extended article in several parts prepared by Pete Soule under the Microaeronautics name. It discusses the properties of the atmosphere and how they affect the flight of aircraft with emphasis on small aircraft. It has an associated industrial strength atmosphere computer program `ATMO99` that can be downloaded and used on any computer running under Microsoft Windows. The program `ATMO99` has been used by two major corporations, most recently in association with the development of a very small GPS guided reconnaissance glider.

This program is described in some detail at the end of the article so that you may decide if you wish to try it. The objective of this article is to acquaint aircraft modelers with the relationship of atmospheric properties such as temperature, pressure, and humidity to the way their aircraft fly.

There is much more to meteorology and aeronautics than is covered here. In particular the aspects of dynamic meteorology that cover the winds and weather in general, yet to understand these effects one must begin with the atmosphere itself. One point of interest to the amateur designer, and one that should be explained here, is that many of the numbers that have appeared in model publications are simply picked or nominal values that pertain to one atmosphere model. There are superior ways to derive the right number for your circumstances, or to test the way changing atmosphere conditions may affect flight characteristics.

This is one of the main things you may come away with from reading this article. I hope that the people who take the time to read this are rewarded with something that they did not know or is interesting to them. If questions come up you can ask. I dont know anything like all the answers but questions often stimulate thought and pose new or interesting problems. The units used are those of the United States Customary System (USCS) and are usually repeated in Systém International (SI) units. In USCS units the abbreviation lbf is used for pounds force to distinguish it from pounds mass. the unit of mass used in the USCS is the slug. Pressure in SI units will be expressed in millibars instead of the more physics-oriented Pascal *Pa* (1*Pa* = 1*N/m2*) .

2 Overview

The atmosphere is the natural element of all things that fly. This article covers the physical properties of the atmosphere affecting model aircraft flight characteristics; for example stalling speed, turning radius, engine power required and developed, and the boundary layer and flow properties that depend on the boundary layer. This article will interpret these effects in terms of atmospheric density, Reynolds number, and humidity. Meteorology, which includes dynamic properties like winds will not be covered, but an understanding of meteorology requires a knowledge of physical properties of the atmosphere.

The dry atmosphere is composed primarily of Nitrogen (78.08% N_2) and Oxygen (20.95% O_2) . The less than 1% remaining is mostly Argon. The CO_2 component (which may produce global warming) is only 0.03%.

This composition, amazingly, is essentially constant over the whole earth from sea level to an altitude of about 250,000 *ft* (76,200 *m*)! Although the molecular composition, except for water vapor, is constant, the density, temperature, and pressure are not.

As a reference point, at sea level a cubic yard of air weighs a little more than two pounds. Helium under the same conditions weighs about 0.27 *lb* which accounts for the buoyant lift of balloons, blimps, and dirigibles. The real atmosphere contains a small but important proportion of water vapor, which will be discussed later.

Many articles in model aircraft-related publications contain formulæto compute aerodynamic forces; drag and lift for example. Usually these mathematical relations have been stated in what one might call"model builder units", such as inches or miles per hour, and involve several numerical constants.

Most of these so-called constants are not really constant, but refer to sea level conditions in something called a "standard atmosphere". The conditions in which you fly models will vary from this standard, sometimes by a significant amount. Here you will find out what the standard is, how to determine the right numbers for your flying conditions, and what the differences mean.

In the early years of aeronautics aircraft performance was difficult to pin down due to a combination of promoters optimism and variations in mechanical and atmospheric conditions when different tests were made. By the 1920s aircraft performance predictions in were made more useful by referencing them to a standard atmosphere - a specification for pressure, temperature and density versus altitude that is consistent with physics.

This standard has been extended, revised, and adopted internationally. It has profited from a great deal of research, culminating in the current international standard as specified in the US Standard Atmosphere 1976. The model for the atmosphere below 80000 *ft* (24384 *m*) is identical to the ICAO standard, an international standard used worldwide by airlines and aeronautical services. In addition, many special atmospheres have been defined for reference that involve the season and latitude. An example would be "midsummer tropical". this is because the variation in aircraft performance and other factors is so great with changes in the atmosphere.

The standard atmosphere, however, is based on a night-and-day average of conditions and a Northern U.SEuropean model for temperature. The gravity model is based on a North latitude of 45°32". The standard sea level temperature of 59°*F* was chosen, in part, because it converts exactly to 15°*C*. The standard atmosphere provides a model for altitudes from below sea level to 1000*km* (*i.e.* about 3.3 million feet), but sea level conditions are usually quoted. The standard temperature decreases steadily from sea level 59°*F* (15°*C*) to a temperature of -69.7°*F* (-56.5°*C*) in the stratosphere, which starts at 36151.5 *ft* (11190*m*). In the stratosphere the temperature remains constant. The next change occurs in the thermosphere, a phenomenon that is out of reach of any model airplane today.

For example the approximate altitude of Colorado Springs is 6000*ft* (1829*m*). The standard temperature at that altitude is about 38°*F*(3.3°*C*). So the standard atmosphere is both too cold and too dry to represent an average flying day for modelers.

The standard pressures for a given altitude can be higher than the true average at many locations. The standard conditions are useful as a comparison reference and that is how it will be used here.

The effects of the atmosphere on model airplane flight (subsonic speeds are assumed) will be discussed below in terms of density, viscosity (Reynolds number, R_e), and humidity considering variations in temperature and pressure.

3 Density

If no trim changes are made, gliders fly faster when the air density is lower. Faster, for example, in Colorado Springs in summer than they do in Minneapolis in winter. Air density is directly related to aerodynamic forces on the aircraft. Maneuverability, (e.g. the number of gs the aircraft can sustain), and, in dry air, the amount of oxygen available for internal combustion engines are directly proportional to atmospheric density.

When variations in Reynolds number,R_e,(treated in section 5 below) are not significant, specific aircraft flight conditions such as wings-level stall, flattest glide, or lowest sink speed occur at a given angle of attack, regardless of the density.

Although the angle of attack for any of these conditions remains the same, the aircraft flight speed for these conditions changes with density. In order to maintain steady or unaccelerated flight, (approximately defined by lift equals weight and constant speed) airspeed at a given angle of attack must go up if density goes down.

Density times airspeed squared must stay constant for an airplane to fly in steady (unaccelerated), level flight. For example, If density is 1/4 of the sea level value then airspeed must be 2 times greater than the airspeed at sea level to keep the angle of attack and maintain unaccelerated flight. Aircraft airspeed indicators, in fact, indicate the equivalent sea level airspeed, not true airspeed. They do this to eliminate the density effect and give an indication to the pilot of what the equivalent sea level conditions are. One of the things we want to know what the density is and how much it varies over possible model flight conditions.

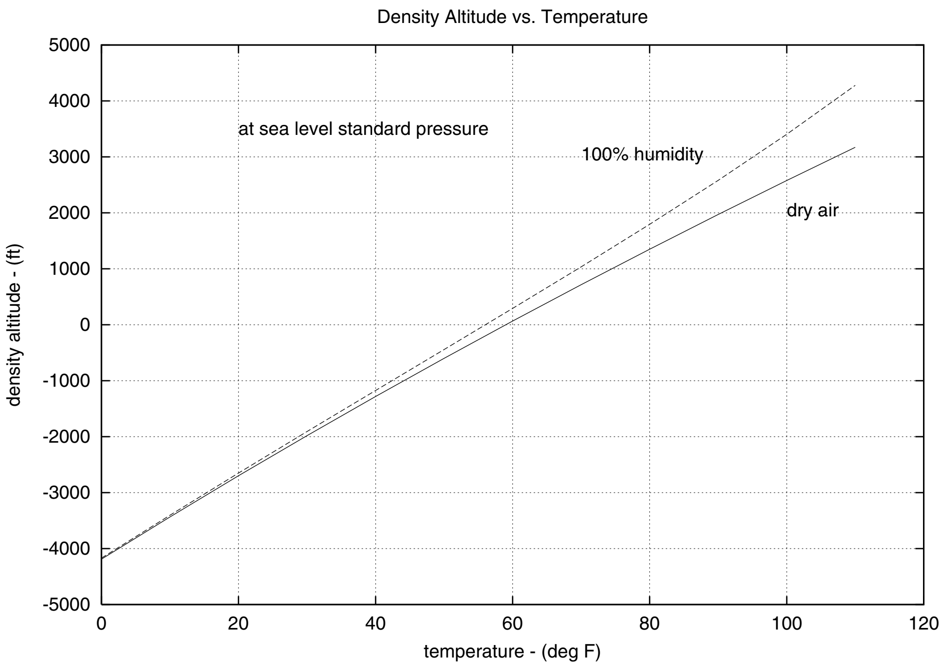
The approximations discussed in the paragraph above have to be modified when density changes rapidly with time as in the case of space shuttle reentry, the SST flying at constant altitude through a pressure gradient, or even the U2 gliding dead-stick from 80000*ft* (24384*m*) (this actually happened, the aircraft flew poweroff for several hundred miles). For model aircraft for the foreseeable future, however, they seem to be just fine.

At the low Mach number that model aircraft fly and when Reynolds number effects can be ignored, the minimum drag in steady level flight does not change with atmospheric conditions. It is the same at all altitudes. This is because the maximum lift-to-drag ratio (L/D) is a constant. When density decreases, however, the speed the airplane has to fly to keep lift equal to weight at the angle of attack for maximum L/D must increase. Because of this the power required to fly at minimum drag increases with decreasing density. If the density is 0.8 times standard density the power required to fly at the same angle of attack will go up by about 12% (*i.e.* the airspeed goes up by a factor of $1/\sqrt{0.8}$.

One convenient way to think about density is to compare the density with the density in the standard atmosphere. A density altitude, H_d, of 3000 ft(914.4 m), for instance, means that the air density is the same as in the density in the standard atmosphere at 3000*ft* (914.4*m*).

If the density altitude is known you can look up density in Table 1 below. Density altitude should normally be within three or four thousand feet of your actual altitude (usually higher), which gives you a good check.

Figure 1 shows H_d for sea level pressure as a function of temperature. You can use `ATMO99` to compute the density altitude exactly for any set of conditions when you have temperature and pressure. Be careful, however, nation-wide meteorology reports show pressures adjusted to sea level. Get the local airfield reading (the altimeter setting for an airfield near you will usually be given in terms of the barometric pressure in inches of Mercury). If all you have is the weather map pressure, the procedure is given in the `ATMO99` manual.



Temperature in Figure 1 is in degrees Fahrenheit - a modeler unit - instead of Kelvins(*K*), the scientific standard, or °*C*. Because atmospheric pressure is still given in inches of Mercury (*inHg*) in most sources in the United States, I have used this barometric unit of pressure measurement here, as opposed to the meteorological standard of millibars.

Note that Figure 1 has two curves. The lower one is for a dry atmosphere, just like the standard atmosphere. The upper curve is for 100% relative humidity.

The effects of humidity are covered in Section 4. As the graph shows, when humidity is considered the density altitude will increase.

Atmospheric pressure normally varies from the standard by -2% to + 1% *inHg*in. Hg at a given location from day to day. Larger variations can occur, for example in the North Pacific Low in winter -4% is not uncommon. Temperature, varies over a larger range. Note that pressures in the rocky mountain west during summer average about 1% below standard.

An example of a large difference, consider two locations: Sea level on a fairly cold winter day in a normal pressure condition (e.g. 30°*F* and 29.92*inHg*) and Colorado Springs at 6560 ft(1999.5 m) altitude on a warm, low pressure summer day: 80°*F* and 23.01*inHg* (779.2 *mb*). The density altitude for these two conditions differs by 12400 *ft* (3779.5 *m*).

In this example the high altitude density is 69% that of the density of the sea level site and gliding speeds are 20% higher. A 300 *s* glide in still air at sea level would take 250 *s* in this high altitude example to cover the same distance.

Table 1 shows some standard atmosphere properties. Pressure is shown in barometric units, density is given in English units; slugs per cubic feet. Multiply the sea level, standard atmosphere speed by the speed ratio to find speed at altitude. As a crude way of measuring the difficulty of flying at high density a power index is listed. It assumes engine displacement must be increased enough to make up for the loss in density, then enough more to fly the plane fast enough to maintain lift at the angle of attack chosen.

Table 1: Standard Atmosphere (1976)
Density Units are *slug/ft²*
Pressure Units are *inHg*

Alt. *ft*	Temp *F*	Pressure	Density	speed ratio	power index
-3000	69.69	33.30	0.002593	0.958	0.878
-2000	66.13	32.14	0.002519	0.972	0.917
-1000	62.56	31.07	0.002447	0.986	0.958
0000	59.00	29.92	0.002377	1.000	1.000
1000	55.44	28.26	0.002308	1.015	1.046
2000	51.87	27.83	0.002241	1.030	1.093
3000	48.31	26.80	0.002175	1.046	1.143
4000	44.74	25.84	0.002111	1.061	1.196
5000	41.18	24.90	0.002048	1.078	1.251
6000	37.62	23.98	0.001987	1.094	1.309
7000	34.05	23.16	0.001927	1.111	1.371
8000	30.49	23.09	0.001869	1.128	1.435
9000	26.92	21.39	0.001811	1.146	1.505

4 Humidity

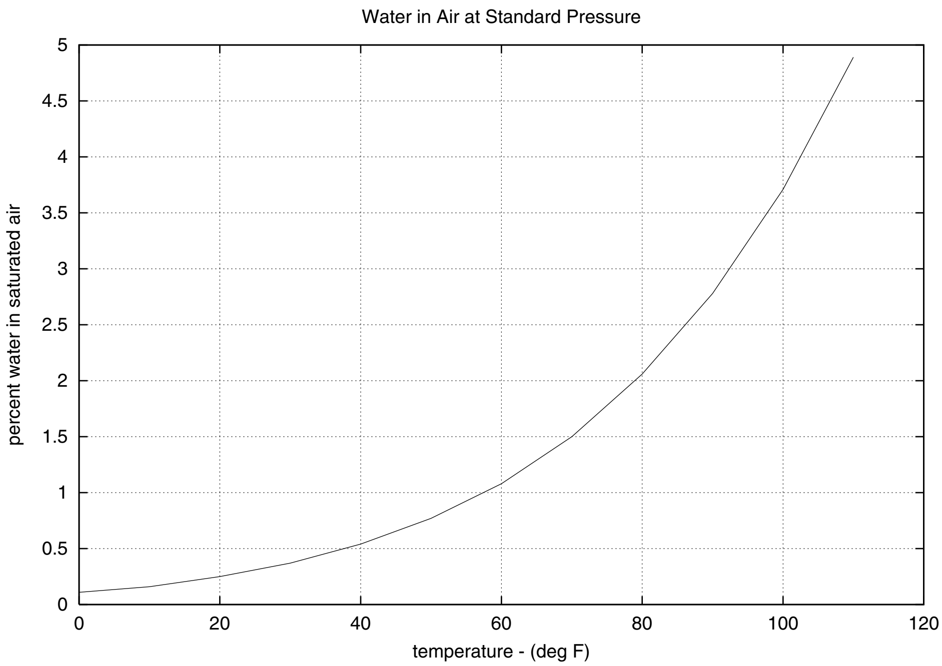
You may have read something that goes like "...the air was heavy with moisture...". The literary idea might be good, but the scientific fact is that at a given pressure and temperature moist air is less dense than dry air. The molecular weight of dry air is 61% greater than that of an H_2O molecule.

The maximum amount of water vapor in the air depends on the temperature and pressure. High temperature and low pressure make the percentage of water mass in the air increase, Remember, though, the standard atmosphere is perfectly dry, free of any water vapor. Because humidity is always present for model builders, this is another factor that changes atmospheric properties for us. Increasing humidity makes both density and Re go down.

The biggest effect is that each molecule of water vapor in the air displaces one molecule of dry air reducing both the amount of oxygen available fo a given mass of air and reducing the density. The maximum power a model aircraft engine can develop is limited by the amount of oxygen drawn in through the intake. The needle valve is opened enough to provide fuel for all the available oxygen, which is directly proportional to the density of the air with the water vapor removed.

Humidity is usually reported as relative humidity in percent. This is the percentage of the mass of water vapor in the air compared to the maximum. Wet bulb and dew point temperatures are also used to measure humidity. The wet bulb temperature is the temperature reached by evaporating water in the air sample until it becomes saturated. At any humidity lower than 100% , the wet bulb temperature is always lower than the ambient. It is the lowest temperature one can get using a perfect "swamp cooler". The dew point temperature is lower than the wet bulb temperature and arrived at by cooling an air sample with a fixed amount of water vapor until it becomes saturated and dew begins to form in the container. With very dry air the dew point, or frost point, is much lower than any low temperature record set on earth, so it is not as intuitively useful a measure as the wet bulb temperature.

The maximum amount of water vapor that can be held by a given volume of air (saturated, or 100% humidity conditions) is a function of air temperature only. The graph below shows the percentage volume the water vapor takes up at sea level pressure. This volume displaces the oxygen the engine needs to generate power.



The standard atmosphere is defined to be dry, however humidity for model flying conditions is often quite high and seldom below 25% or so. As a consequence humidity corrections to dry atmosphere data can be important.

The volume of air being drawn in by an engine is limited by its displacement and induction system. The oxygen available to burn is proportional to the density times the volume of dry air drawn in. Variations in density were discussed earlier. When the air is humid some of the volume is taken up by water molecules as shown in the graph above.

For engine power corrections, then, both the density and humidity have to be taken into account and, because the maximum quantity of water vapor depends only on temperature, air at a given relative humidity will have a higher percentage of water mass when the temperature is high and the pressure low. In other words, the water displaces more dry air at these conditions, even though the relative humidity is the same.

As an extreme example, consider flying at standard sea level pressure, 29.92*inHg* (1013.2 *mb*) but at 90°*F* (32.2°*C*).

In this case the Density altitude for dry air is 1972 *ft* (601.1 *m*). At 100% humidity the density altitude is 2581 *ft* (786.7 *m*). The density is 93% of standard, but because the water molecules displace the air molecules the mass of oxygen for a given volume of air is only 90% of sea level standard.

All the calculations above can be accomplished accurately with the program `ATMO99`.

5 Reynolds Number

This section might properly be titled air viscosity effects. Of most importance to free flight, R/C gliders, and propellers, the Reynolds number (R_e) represents the ratio of inertia forces to viscous forces in the airflow around the aircraft. Variations in Re can have a profound effect on the boundary layer and flow separation. The $R_e$values for model flight range roughly from 100 for indoor models and control line wires, to 1,000,000 in R/C pylon racing. The rule of thumb is: low Reynolds numbers are bad for aerodynamics. Wind tunnel data are classified according to $R_e$so if you make reference to these data it is important to be able to estimate R_e.

Wakefield flier Fred Pearce pointed out the practical importance to me. His thoroughly tested model was flown at a contest in "high and hot" conditions and had to be retrimmed to recover anything like the expected performance. When he got home he computed the horizontal tail $R_e$at the flying site conditions and found it was low enough to have become sub critical.

The formula for $R_e$found in model magazines is almost always based on sea level standard, yet $R_e$can vary by up to 40% from sea level standard conditions, and is almost always lower than it would be in the standard atmosphere. Atmospheric temperature has the largest effect on R_e, density differences due to altitude and humidity will also change Reynolds number.

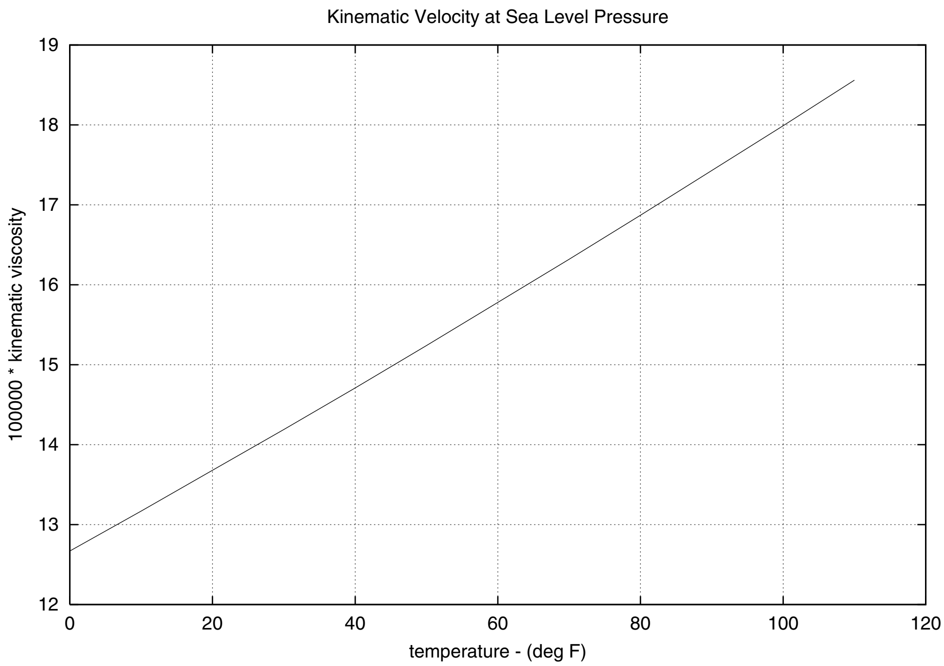
For power model propellers there is an important $R_e$effect. Low Re reduces critical Mach number, which can vary from 0.5 to 0.7 depending on section and R_e. The drag rise starts at this Mach number accompanied by shock-induced separation. Some racing propellers operate close to or over the critical Mach number, some are even slightly supersonic, and take a big hit in efficiency. Military R/C drones also have had trouble with the combination of high tip Mach numbers and low Reynolds numbers. Other than geared engines, propellers with lower diameter, more and/or wider blades are the only fix for this problem.

The formula to calculate $R_e$is given below. In this relation V is the velocity, *i.e.* airspeed, and l is a length (for airfoils the chord is usually chosen). The Greek letter mu, μ, represents the dynamic viscosity and the Greek letter nu, ν is the kinematic viscosity.

$$\nu \stackrel{\text{def}}{=} \frac{\rho}{\mu}$$

$$R_e = \frac{Vl}{\nu} = \frac{Vl\mu}{\rho}$$

Either low density or high temperature will reduce the R_e. If the "characteristic length", l, is measured in feet, and the velocity, V, in feet per second, Figure 2 shows the value of kinematic viscosity to use.



An example, using the Figure, follows:

Velocity 70*mi/hr* = 102.7*ft/s*

Chord 10.0*in* = 0.833*ft*

Pressure 29.00*in*Hg

Temperature 85*F*

From Figure 2 find standard pressure dynamic viscosity = 1.725 x 104 = 0.0001725

Correct for pressure (29.92/29.00)*0.0001725 = 0.000178

Compute R_e= 102.7.0 x 0.833 / 0.000178 = 480,000

Note that $R_e$can vary over a larger percentage range than density. In the example given in the previous section (the Colorado Springs example), the kinematic viscosity in the high/hot condition is 1.56 times the socalled standard value found in the sea level standard atmosphere and a large number of text books.

6 Closure

Aerodynamic formulæpublished in model magazines often contain constants based on a standard atmosphere at sea level. In general the density and Reynolds number predicted using these constants will be too high for model aircraft flight. If you live at any appreciable altitude above sea level, fly in the summer, and/or in humid air the predictions using sea level conditions can be significantly in error. If you want to make some approximate calculations and you dont have the pressure, approximate it by the pressure in the standard atmosphere at your altitude but use the temperature you expect to fly at. Try two other cases with the high/low percentage pressure variation.

Look at the graphs for dry air again and remember that humidity can reduce density by 1% or 2%. This reduction also applies directly to Reynolds number.

Engine power - internal combustion engines at least - will be affected even more. If you fly electric powered aircraft the hit wont be so bad. If you like to look at numbers or use computers the program `ATMO99` described in the section [`ATMO99` Computer Program] and runs under Win95, Win98, WinMe, WindowsNT, Windows2000, and WinXP may be of interest.

The Atmosphere you fly in plays an important part in the performance of your model, but even though high altitude degrades performance some models have gone far beyond the range of variables discussed here. Maynard Hills radio control model aircraft world record, set in 1970, is 26,900*ft* (8199.1*m*). The outer edge of performance.

Maynard Hill has the support of the Johns Hopkins University Applied Physics Laboratory (JHUAPL) to set the record. You need a government lab to measure the altitude and to help see the model to fly it. Only model designing, building and flying skills, however, will help fly in the zero or sub zero temperatures and density at that altitude is only 42% of sea level standard. Even the free flight helicopter word record set in 1963 by Stefan Purice of Romania is 12,300*ft* (3749.0*m*)! You might like to guess how he did it.

Significant increases in altitude above the current record may not come this century not only because the because the cost and technical challenges are legion but also interest in setting a record when you cant see your model fly is certainly low.

How hard it is might be realized by examining well-financed efforts of somewhat larger aircraft. For instance, consider the slightly amusing but, as Wayne (from Waynes World) would say, “Bogus and also sad”, experience of the 1.5 million dollar NASA Perseus project: Perseus, somewhere in size between a small man-carrying glider and a giant scale model, was called a “pathbreaking but controversial effort to use inexpensive robot aircraft ...” (Los Angeles Times, December 4, 1994).

Although it was promised to fly to 98000*ft.* 35000*ft* was the actual achievement at which point it broke apart in midair. (International ruled require the aircraft to return in order to set a record.) They shoulda asked JHUAPL and Maynard for advice. (Meanwhile we need to redefine “inexpensive”).

In terms of dollars per foot, Maynard Hills achievement, on view at the AMA museum, is all the more impressive. Aside from world records, what would be interesting is to hear from modelers who fly in extreme conditions. I have flown in Yellowstone Park at 7000*ft* (I lived there at the time and flew gliders. Not advisable for power models!). In Alaska, doing time in the Air Force during the Korean war, I gave up flying when winter really set in, but surely there are many who fly on under such daunting circumstances. Estimate the density altitude at your flying site during the climactic extremes of the year. If you fly very small models or use wind tunnel data, check the variation in R_e.

7 References

References used for physical constants and models are:

1 ***The International System of Units***: E.A. Mechtly *NASA SP-7012 U.S. Government Printing Office*, Washington, D.C,. 1969

2 ***The U.S. Standard Atmosphere (1976)***: Annon *N.B.S. Publication U.S. Government Printing Office*, Washington, D.C,. 1978

3 ***Defining Constants, Equations and Abbreviated Tables of the 1975 U.S. Standard Atmosphere***: R. A. Minzner *et. al. NASA TR R-459 NASA*, Washington, D.C, 1976

Several general references that are in relatively inexpensive paperback form have been issued by Dover Publications. A sampling of those that contain some material on both atmospheric properties and aerodynamics is given below :

A relatively advanced book on dynamic meteorology, The Ceaseless Wind, contains a modern thermodynamic treatment of atmospheric gasses and the effect of humidity. Two other undergraduate college-level references are also given. These latter references and several other similar ones provide a good background and, in addition, discuss practical climate conditions and many other topics of interest to flying models.

4 ***The Ceaseless Wind***: J.A Button, *Dover Publications, Inc.* Mineola, NY, 1986

4 ***Atmosphere, Weather and Climate***: R.A.G. Barry & R.J. Chorley 6th edition. *Routledge* London, U.K., 1992

5 ***General Meteorology***: H.R. Beyers 4th edition *McGraw-Hill* New York, 1974

6 ***Theory of Flight***: R. von Mises *Dover Publications, Inc.* Mineola, NY, 1970

Reference 6 is written at the junior/senior year college level that gives insight to the standard atmosphere development and use prior to and during World War II is available as a reprint of the original McGraw Hill book. It is written by a famous author, Richard von Mises, who made major contributions to several scientific fields and published the first set of lectures on flight mechanics.

In addition a treatment of aerodynamics first published in Germany before W.W.II and presented at an intermediate level which includes atmospheric physics is in the second volume of a two volume set.

7 ***Fundamentals of Hydro and Aeromechanics***: L. Prandtl and O.G. Tietjens 2 vols. *Dover Publications, Inc.* Mineola, NY, 1970

These little books are of special interest because one of the authors is Ludwig Prandtl, a great pioneer in aerodynamics who played the major role in generating the modern foundation of subsonic aerodynamics.

