Aerobasics – An Introduction to Aeronautics

2. The Atmosphere

S P Govinda Raju

Aircraft of all types dynamically interact with the atmosphere generate forces required for lift and propulsion. Properties of the atmosphere and their variations over geographic locations and altitude are thus relevant to aircraft flight operations. This article presents some facts about the atmosphere and indicates their relevance to flight.

S P Govinda Raju retired as professor from the Department of Aerospace Engineering, Indian Institute of Science in 2003. He is currently active as a consultant in wind tunnel testing and teaches short term courses in aerodynamics and flight mechanics.

1. Introduction

The earth is roughly a sphere of about 12,700 km in diameter. Surrounding it is a thin layer of air whose upper limits are not well defined but about 95% of the total air mass is contained in the lowest 20 km of the atmosphere. It is only in this layer that aircraft of all types operate. Properties of primary interest are air density, pressure and temperature and their variation with altitude. This atmosphere is nearly transparent to sunlight and is mainly heated from below by contact with the ground which absorbs the solar radiation. Solar radiation has a diurnal cycle and also varies with latitude and season. As a result, there are spatial and temporal variations in temperature which result in convection currents being set-up in the atmosphere. The maximum temperature of the air generally occurs close to the ground and it decreases with altitude. The vertical profile of the temperature depends on the latitude as well as season, with marked differences between the tropics and polar regions. As a useful approximation, it is possible to define a reference atmosphere which represents the annual mean conditions at a latitude of around 45 ^{o}N. This is termed the International Standard Atmosphere (ISA). The actual atmospheric conditions at a particular place and time could be significantly different from ISA and need to be considered.

Keywords
International Standard Atmosphere, Indian reference atmosphere, pressure altitude, atmospheric humidity, icing, gusts and winds.

Box 1. The Pressure Altitude

When in flight, an airplane pilot has to know his altitude, the geometric height above a reference, generally the mean sea level. This is necessary to avoid flying at the same altitude as other aircraft in the neighborhood (with which his airplane could collide) and to avoid flying into ground or other terrain (hills). The altitude is measured using an instrument called the pressure altimeter. The pressure altimeter measures the atmospheric pressure in the neighborhood of the airplane and converts this into an altitude reading by using the relation between pressure and altitude in the ISA. This reading is the pressure altitude which can be somewhat different from the geometric altitude except when the atmospheric conditions up to the flight altitude are exactly as in the ISA. The difference could be significant especially during takeoff and landing of aircraft, and corrections are generally applied when operating near airports by knowing the actual atmospheric pressure and altitude at the airport. When operating away from airports, no corrections are applied and flight pressure altitudes are referred to as flight levels. As an illustration, an aircraft flying at a pressure altitude of 15,000 feet is referred to as flying at FL 150. It may be noted that there is no possibility of two aircraft colliding unless they fly at the same flight level. This is because the pressure of the atmosphere varies monotonically. The same is not true of temperature and a temperature altitude exhibits wide variations with respect to geometric altitude and is not a useful concept.

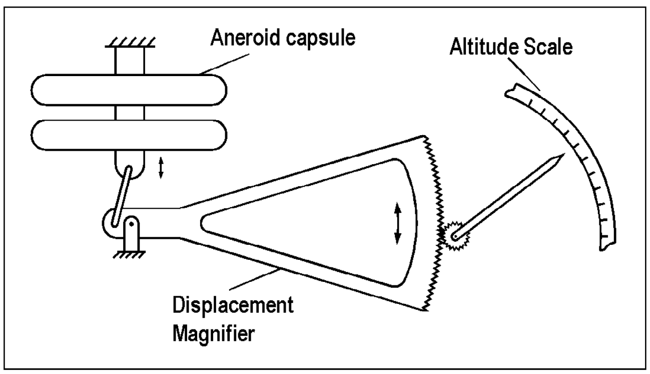


Figure A: The pressure altimeter.

The schematic diagram of an instrument to indicate the pressure altitude is shown in *Figure* A. It consists of a pressure sensitive element in the form of two evacuated chambers with corrugated circular diaphragms for the walls. The diaphragms are elastic and deform due to the atmospheric pressure acting on the outside. This deformation is magnified by a set of levers and gears and indicated on a scale graduated in terms of altitude. All aircraft carry at least one such instrument.

The ISA is based on an atmosphere in static equilibrium. Thus the pressure at any point in it is equal to the weight per unit area of the air column above that point. This weight depends on the density of air which in turn depends on temperature. The ISA assumes that the temperature at sea level is 15 ^{o}C, and that it falls

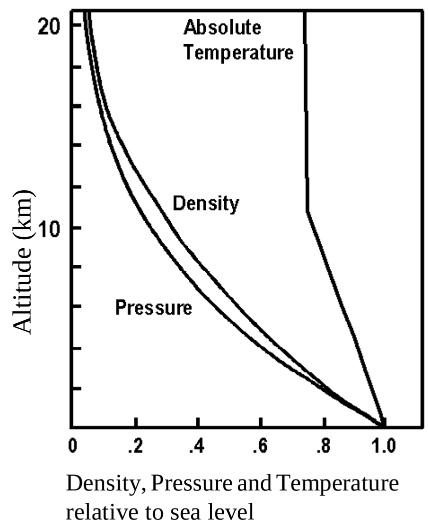
Box 2 Aircraft Pressurization

Human beings are comfortable only over a narrow range of atmospheric pressures and temperatures. Typically this range is 0.75 to 1.0 bar pressure (a bar = 10^5 Pa and is very close to sea level atmospheric pressure) and 20^o to 30^oC temperature. As the atmospheric pressure and temperature vary greatly with altitude, the comfort of passengers traveling in aircraft can be ensured only if the air inside the aircraft is maintained within the above range independently of the conditions outside the aircraft. As modern jet aircraft fly at about 11 km altitude for reasons of economy, and at this altitude the pressure and temperature of air are roughly 0.25 bar and -40^oC, it is imperative that the passenger cabin be supplied with air conditioned to be within the comfort limits. It is the normal practice to keep the internal pressure of the passenger cabin at or above 0.75 bar which corresponds to a pressure altitude of about 2500m.This is done by compressing and conditioning the outside air before supplying to the passenger cabin. The compressed air required for this purpose is often obtained by bleeding the compressors* of jet engines which power the aircraft.

Is to be noted that at the cruise altitude, the pressure inside the passenger cabin (the fuselage) is 0.75 bar while it is about 0.25 bar outside. Thus the walls of the fuselage are subjected to a differential pressure of 0.5 bar in cruise. When on the ground, this differential pressure vanishes as the outside pressure rises to the atmospheric pressure at the airport. Thus every flight results in one cycle of pressurization of aircraft fuselage. During the life of a typical passenger aircraft, the number of these loading cycles could exceed 50,000 and aircraft fuselages are designed for this cyclic loading. The first jet passenger aircraft, the Comet, did not meet this requirement. However, this was not clearly recognized at the time. This led to structural failures (explosions) of the fuselages of a few Comet aircraft during flight with disastrous consequences. A major engineering effort was required to identify and solve this problem.

* An aircraft jet engine draws a large mass of air (typically over 100 kg/s) into its compressor and raises its pressure many times before sending it successively through a combustion chamber, a turbine and a nozzle which finally produces a propulsive jet. A small part of this air is taken out (bled) from the compressor at a suitable stage of compression, conditioned further (heated or cooled) and used for pressurizing the passenger cabin.

uniformly at a rate of 6.5 ^oC per km with altitude up to 11 km, and then a constant temperature of –56.5 ^oC up to 20 km. Beyond 20 km altitude there is a slow rise of temperature. *Figure* 1 shows the properties of this reference atmosphere. Atmospheric conditions over India are generally warmer than in the ISA and it is usual to base the performance estimates of aircraft on a reference atmosphere which is warmer than the ISA by 15 ^oC at sea level and the temperature falling at the rate of 6.5 ^oC per km up to 15 km and remaining constant beyond 15 km. This temperature profile is compared with the ISA in *Figure* 2.



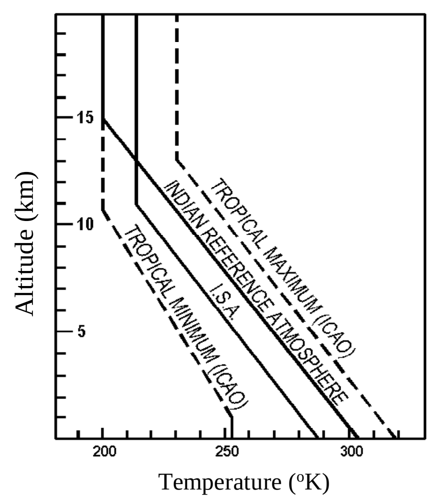


Figure 1 (top). International Standard Atmosphere (ISA): It is based on a sea level temperature of 288 °K and a lapse rate of 6.5 °C per kilometer of altitude. The nearly exponential fall in pressure and air density may be noted.

Figure 2 (bottom). Air temperatures over India: Compared to ISA, the Indian reference atmosphere is 15°C warmer at low altitudes. The maximum temperature can occasionally be as high as ISA + 35°C. As aircraft engines lose power at high ambient temperatures, performance of any aircraft is adversely affected under this condition. Its take-off weight may have to be restricted on this account.

Box 3. Altitude and Aircraft Performance

Aerodynamic forces on aircraft wings and power produced by the engines of all types are directly dependent on the density of air around them and hence decrease with altitude, other things being the same. Thus every aircraft has a ceiling beyond which it cannot climb for want of lift or engine power. The altitude record for airplane flight is around 30 km, but many aircraft can reach only around half this altitude or less. The cruise altitude of an aircraft is determined by economic considerations and is around 11 km for any large civil aircraft. The supersonic transport, the Concorde, cruised at about 20km altitude. Smaller aircraft equipped with reciprocating engines and propellers, cruise at less than 3 km altitude.

2. Atmospheric Humidity

Air can contain water vapor and the maximum quantity depends strongly on air temperature and pressure. In the extreme case of a relative humidity of 100% at sea level with an air temperature of 40 °C, the water content in air is less than 5% by weight. Humid air is slightly lighter than dry air but the difference is not important from the point of view of flight mechanics. However, many atmospheric phenomena like fog, rain and snow, icing and vertical atmospheric motion including cloud formation are the result of the phase transformation of water vapor in the atmosphere[1] and these affect aircraft operations.

[1] Atmospheric air is generally humid and contains some water vapor which is not sufficient to saturate it. This is indicted by its relative humidity being less than 100%, the value corresponding to saturation. When humid air is cooled, it reaches saturation at a temperature which is called the dew/frost point. On further cooling, water condenses out in the form of water droplets or ice crystals. When this happens in the atmosphere, we have fog or snow.

Fog is due to the condensation of water vapor from air due to cooling near the ground and generally occurs when air cools below the dew/frost point temperature (generally early in the morning). Fog can also result from advection of warm and moist air (e.g., from a water body like the sea) to a colder (e.g., land) region. Fog reduces visibility and can prevent safe take-off and landing. Instrument landing systems (ILS) have been developed to overcome this problem.

Under suitable weather conditions, snow accumulates on runways and on parked aircraft and needs to be cleared by mechanical means before an airplane can be permitted to take-off. Similarly, deposition of ice on the aerodynamic surfaces (like wings, tail planes, propellers and engine inlets) of an aircraft in flight can take place and affect its performance adversely. Many aircraft accidents have been attributed to this cause. Ice formation on aircraft surfaces is most likely in the temperature range of 0 °C to –30 °C and occurs only below 6.7 km altitude. The air is too dry and too cold at higher altitudes to be a problem. Suitable protection systems against icing are often provided on aircraft.

Small aircraft with piston engines or turboprops are particularly prone to icing as they operate for extended periods at altitudes where icing is possible. In these aircraft, protection against icing in flight is provided for. Windshields and leading edges of propellers are electrically heated in icing conditions. Leading edges of wings and tail planes are provided with inflatable rubber boots (which when pressurized crack and dispose off any ice accumulation). Engine exhaust gas of piston engines is used for heating their carburetors to prevent ice build-up at their throats.

Lightning, the discharge of static electricity in clouds, through an aircraft in flight needs consideration, specifically in the case of aircraft made of composite materials (which are poor electrical conductors). Suitable conducting paths have to be provided to avoid structural failure due to lightning. Electromagnetic shielding of avionics of the aircraft is also an important consideration.

3. Winds and Gusts

Atmospheric air is seldom motionless and winds of few meters per second are present most of the time near the ground and in the lower altitudes (below 4 km). A strong wind, 30m/s or higher, occurs very rarely and is associated with a tornado or a hurricane. Steady winds are also found at higher altitudes. A special type of high altitude wind with steady speeds of up to 100 m/s occurs near latitudes of 30 ^{o}N and 60 ^{o}N flowing as a meandering stream from west to east at an altitude of 6–12 km and is named the jet stream. A jet stream is typically a few kilometers deep, several tens to hundreds of kilometers wide and a thousand or more kilometers in length. Recently, a balloonist used the jet stream to circumnavigate the globe.

Steady winds affect aircraft only to the extent of changing their speed relative to the ground (ground speed) as aircraft maintain their air speed (the flight speed relative to the air mass in which they travel) at suitable operational levels without regard to wind speeds. Thus, for example, a tail wind[2] can increase the ground roll on take-off and landing as the airplane lands at a higher ground speed than normal. A head wind[2] has the opposite affect on landing and take-off.

A gust is a wind with a significant vertical component extending over a relatively small region, typically less than a kilometer in

[2] A wind can blow from any direction relative to the airplane flight direction (heading). A wind coming head on towards the airplane, the head wind, increases the air speed for the same ground speed. This is safer during take-off and landing as the airplane takes off or lands at a lower speed relative to the ground. A wind blowing along the flight direction, the tail wind, has the opposite effect and is best avoided by proper choice of runway direction. A wind having a significant component in a direction perpendicular to the flight direction, the cross wind, creates problems in landing as the airplane tends to drift across the runway and this has to be overcome by an appropriate application of lateral control (rudder).

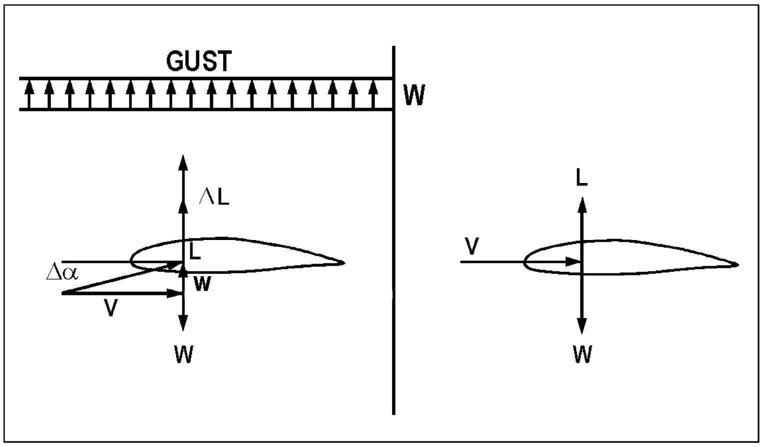


Figure 3. A wing penetrating a gust: There is a sudden change in incidence and a corresponding change in lifting force. This induces a transient motion of the airplane during which there is a vertical acceleration and this causes discomfort to passengers and also imposes additional loads on the wing.

size. Gusts are more intense in the lower altitudes with vertical speeds up to 15m/s. When an airplane in steady level flight enters a gust, its wing experiences a sudden change in incidence as shown in *Figure* 3. This results in a sudden change of lift and induces a vertical acceleration which dies out over time. The vertical acceleration affects passenger comfort and imposes additional loads on the wing structure. These loads need to be considered in the design of the aircraft structure.

Winds generally vary slowly with altitude. A rapid variation of wind with altitude sometimes occurs during stormy weather and is termed the wind shear. Wind shear can create a hazard to flight particularly during take-off and landing. An aircraft climbing or descending through a wind shear experiences a rapid change of airspeed (the air flow velocity relative to the airplane and hence the wing lift) and this affects its flight path and can lead to a crash.

Address for Correspondence
S P Govinda Raju
Department of Aerospace Engineering
Indian Institute of Science
Bangalore 560 012
India
Email: spg@aero.iisc.ernet.in