PART 1 : SECTION 1

CHAPTER 2

MEASUREMENT OF SPEED

Density of Air

1. The weight of a cubic foot of air at sea level is about ·08 lb., or about $1\frac{1}{4}$ oz. The comparatively large volume and low weight means that the density (the amount of mass per unit volume) is low. The same volume of water weighs $62\frac{1}{2}$ lb. and accordingly the density is much greater as a greater mass is contained in the same amount of space.

2. **Static Pressure.** The static pressure of the air is the pressure exerted by the air by virtue of its weight. At a given point in the atmosphere the local static pressure acts equally in all directions.

3. **Movement of Air.** For the purpose of aerodynamic demonstration, it is immaterial whether air is moving past a stationary object, whether an object is moving in still air, or whether an object is moving in air which itself is in motion. The relative velocity (V_R) is the difference between the velocity of air (V_a) and the velocity of the object (V_o), *i.e.* $V_R = V_a \sim V_o$.

Dynamic Pressure

4. Because it possesses density, air in motion must possess energy and therefore exerts a pressure on any object in its path. This dynamic pressure is proportional to the density and the square of the speed. The energy due to movement, the kinetic energy (K.E.), of one cubic foot of air moving at a stated speed is given by the following formula :

$$\text{K.E.} = \tfrac{1}{2}\rho V^2 \text{ foot pounds}$$

where ρ is the local air density in slugs per cubic foot and V is the speed in feet per second.

If this volume of moving air is completely trapped and brought to rest by means of an open-ended tube the total energy remains theoretically constant (in practice small losses are incurred because air is not an ideal fluid). In being brought to rest the kinetic energy becomes pressure energy which for all practical purposes is equal to $\frac{1}{2}\rho V^2$ lb./sq. ft., or if the area of the tube is S sq. ft., then :

$$\text{Total pressure} = \tfrac{1}{2}\rho V^2 \text{ S lb.}$$

5. A calculation of the pressure energy of moving air by this expression alone applies only to air which is brought completely to rest in an open-ended tube pointing directly into the air stream so that all the air is trapped. When the air impinges on a flat plate at right angles to the flow the air particles tend to spill around the edges of the plate, and the use of the $\frac{1}{2}\rho V^2 S$ formula alone is no longer valid. This aspect of the resistance caused by air movement is dealt with in Chapter 3, "Drag".

6. The term $\frac{1}{2}\rho V^2 S$ is common to all aerodynamic forces and fundamentally determines the air loads imposed on an object moving through the air. It is often modified to include a correction factor or coefficient. The term stands for the dynamic pressure imposed by air of a certain density moving at a given speed and which is brought completely to rest by an object of a stated area. The abbreviation for the term is the symbol "q".

Principle of the Air Speed Indicator (A.S.I.)

7. It is essential that an aircraft has some means of measuring the speed at which it is passing through the air. The A.S.I. is the instrument used for this purpose. The instrument in its most simple form is operated by pressures picked up by a pressure-head which is mounted at a suitable position on the aircraft. An elementary pressure-head consists of an open-ended tube (the pitot tube) which faces the direction of flight, and a second tube (the static tube) which is closed at the forward-facing end but has a series of small holes drilled radially along its length ; the static tube is not affected by dynamic pressure as the end is closed, but the small holes, flush with the surface, are sensitive to the local static pressure.

8. The pitot tube experiences a total pressure made up of the static pressure and dynamic pressure. The total pressure is led through a pipeline to one side of a chamber which is divided by a thin flexible metal diaphragm. The static pressure is led similarly through a separate pipeline to the other side of the diaphragm.

9. In the chamber the diaphragm is subjected to the two opposing pressures. However, that part of the total pressure which is made up of static pressure is cancelled by the static pressure in the other chamber. Thus the amount of any diaphragm movement is determined purely by

the dynamic pressure. Movement of the diaphragm is transmitted through a system of levers to the needle of the A.S.I. The instrument therefore reads the difference between the two measured pressures and indicates dynamic pressure in terms of speed, the indicated speed varying approximately as the square root of the dynamic pressure.

Indicated and True Air Speed

10. The A.S.I. can be calibrated to read correctly for only one density/altitude. All British A.S.Is. are calibrated for I.C.A.N. sea-level density; under these conditions, at a given *true air speed* (T.A.S.) and at standard sea-level density, the A.S.I. shows an *indicated air speed* (I.A.S.) equal to the T.A.S.

11. At some greater altitude, say 20,000 feet, the density is much reduced and, *at the same T.A.S.*, this results in a lower dynamic pressure (the $\frac{1}{2}\rho V^2$ effect is reduced) and so the I.A.S. is reduced in the same proportion as the drop in density. Thus at 40,000 feet, where the standard density is half the sea-level value, the A.S.I. will indicate a speed approximately half the T.A.S., the approximation being caused through errors discussed in later paragraphs.

12. The magnitude of the difference between I.A.S. and T.A.S. depends entirely on the density and therefore grows larger as the altitude increases. An extreme example of this characteristic of the A.S.I. is given by considering the V.2 rocket at the peak of its trajectory at some 300,000 feet; while the T.A.S. is some 2,000 knots, the very low density results in a dynamic pressure sufficient to give a theoretical I.A.S. of only about 4 knots; thus the air loads on the structure are equivalent to those set up at sea level by a 4-knot wind.

13. From the foregoing it can be seen that only at sea level does the A.S.I. indicate a required T.A.S., and at all other altitudes the I.A.S. falls in proportion to the drop in density.

14. Although the A.S.I. is accurate as a measure of true speed only at sea level, the I.A.S. is an important figure during flight. The air loads on an aircraft in level flight or during straight dives and climbs are directly proportional to the dynamic pressure and thus to the I.A.S. An aircraft which is flying at an altitude of about 75,000 feet at a T.A.S. of some 1,300 knots has a corresponding I.A.S. of about 270 knots; therefore, although the T.A.S. is high, the forces experienced on all parts of the airframe are the same as those which they would experience at sea level at a T.A.S./I.A.S. of about 270 knots. It is partly for this reason that high-speed research is carried out at the greatest possible altitudes.

15. The air loads on the airframe in level flight or in straight dives or climbs are therefore determined by the I.A.S.

Errors of the Air Speed Indicator

16. The A.S.I. is subject to the following errors:—

(*a*) Instrument error.

(*b*) Pressure error.

(*c*) Compressibility error.

Faults may occur which are associated with blockages and leaks of the pipeline system between the pitot tube, static vent, and the instrument. These are discussed in Part 2.

17. **Instrument Error.** Instrument error is caused by minute differences in construction. The extent is determined by comparing individual instruments against a master calibrator. The error is usually very small and is included in the P.E.C. figures displayed in the cockpit of individual aircraft. The P.E.C. figures given in Pilots' Notes, however, do not include instrument error since it varies from instrument to instrument.

18. **Pressure Error (P.E.).** Pressure error was previously known as position error and reference to it by this name may still be found. P.E. is caused by the effect of the movement of the aircraft on the static pressure prevailing in the immediate vicinity of the aircraft. The magnitude of the pressure error correction (P.E.C.) depends on the position of the static source and the indicated speed of the aircraft. The pressure error for a particular type of aircraft is determined by practical experiments throughout the speed range of the aircraft, and corrections for sea level are given in tabular form in the Pilots' Notes for each aircraft. The P.E.C. tables given in Pilots' Notes apply only to sea-level conditions. It should be noted that, when cruising at high mach numbers (see paras. 24 to 27) compressibility effects may cause considerably greater errors which would have an effect on range if not allowed for. At a given I.A.S. large variations in the aircraft weight may also have an appreciable effect on P.E.

19. **Compressibility Error (C.E.).**

(*a*) The general principle of air speed measurement is that part of the air stream is brought to rest relative to the aircraft and, in being brought to rest, generates a pressure which, for a given density, is a function of the I.A.S. The A.S.I. interprets and indicates this pressure in terms of air speed, but if the instrument does not compensate for compressibility a faulty I.A.S. is obtained.

(*b*) It can be shown that if two streams of fluid having the same speed and density are brought to rest, one fluid being compressible and the other incompressible, then the pressure generated in bringing the compressible fluid to rest will be greater than the other.

(*c*) Since air is a compressible fluid it will compress when brought to rest in a pitot tube. The higher pressure recorded in the A.S.I. as a result of compressibility is interpreted by the instrument as a higher I.A.S. Thus C.E. causes the A.S.I. to over-read, and therefore compressibility error correction (C.E.C.) is always negative.

(*d*) *Compressibility and Density.* Air of low density is more easily compressed than air of higher density. Thus air near sea level is more resistant to compression than air at, say, 40,000 feet. At an altitude of 5,000 feet, the dynamic pressure corresponding to an I.A.S. of 300 knots causes a C.E. of 2 knots, but at 40,000 feet the same I.A.S. causes a C.E. of 25 knots. The compressibility correction table below gives the C.E.C. for altitudes up to 50,000 feet and indicated air speeds up to 600 knots.

Rectified Air Speed (R.A.S.)

20. When the I.A.S. has been corrected by the application of P.E.C. and, if necessary, instrument error correction, the result is known as the *rectified air speed* (R.A.S.). The R.A.S. does not include C.E.C., therefore, when computing the T.A.S., it may be necessary to apply C.E.C. before proceeding with the computation. Paras. 21 to 23 state when it is necessary to apply the C.E.C. to obtain a corrected R.A.S.

Calculation of T.A.S.

21. **Mk. 2A and Mk. 4 Height and T.A.S. Computers.** *When using either the Mk. 2A or the Mk. 4 Height and T.A.S. Computer it is not necessary to allow for C.E.C.* Both these computers have a built-in correction for C.E. and *no separate allowance must be made for it.* However, P.E.C. and instrument error correction must be made, *i.e.* R.A.S. must be used for the calculation.

22. To calculate the T.A.S., using a recognized service computer other than those specified in para. 21, the C.E.C. must be determined from the table in para. 19 and subtracted from the R.A.S. to obtain the correct figure with which to start the computation.

23. **Computation of T.A.S.—Method 2.** Fig. 1 shows diagrammatically how the T.A.S./R.A.S. ratio varies with altitude. To calculate the T.A.S. from this chart the C.E.C. must be applied to the given R.A.S. before proceeding any further. The corrected R.A.S. is then multiplied by the appropriate value on the vertical scale of the graph. The centre curve refers to standard

COMPRESSIBILITY CORRECTION TABLE

Subtract Correction from Rectified Air Speed

Not applicable to the Mk. 4A and Mk. 4 Height and T.A.S. Computers

Altitude (feet)	R.A.S. (Knots)									
	150	200	250	300	350	400	450	500	550	600
S.L.	0	0	0	0	0	0	1	2	2	3
5,000	0	0	1	2	2	3	5	6	8	10
10,000	0	1	2	3	5	7	10	13	17	21
15,000	1	2	3	5	8	12	16	21	27	
20,000	1	3	5	8	12	17	23	31		
25,000	2	4	7	11	17	24	32			
30,000	2	5	9	15	23	32				
35,000	3	7	12	20	29					
40,000	4	9	16	25						
45,000	5	12	21	33						
50,000	7	14	25							

atmosphere conditions and those on either side to tropical summer and sub-arctic winter conditions. For example, an R.A.S. of 250 knots at 25,000 feet, corrected for C.E., gives 243 knots. Reference to the curves gives 1·5 × 243 = 364 knots (approximately) under standard atmosphere conditions at a temperature of about −35°C., and about 1·4 × 243 = 340 knots (approximately) at a sub-arctic temperature of about −50°C.

Mach Number

24. **The Machmeter.** An additional means of measuring speed is the *machmeter*. This instrument indicates continually at what fraction of the local true speed of sound the aircraft is flying. The indicated figure is the mach number (M) at which the aircraft is flying.

25. **Variation of the Speed of Sound.** The speed of sound varies as the square root of the absolute temperature. The speed of sound, therefore, decreases as the temperature falls with altitude. In standard atmosphere conditions the speed of sound is 661 knots at a temperature of 15°C. at sea level, while in the stratosphere above 36,000 feet the temperature is −56·5°C. and the speed of sound 573 knots.

26. An indicated ·7M at sea level at standard temperature means that the aircraft is flying at ·7 × 661, or about 463 knots. The same mach number at 40,000 ft. gives a T.A.S. of ·7 × 573, or about 400 knots. Thus, although the aircraft is flying at the same indicated mach number (I.M.N.), the fall in temperature with altitude means that to keep constant the ratio of the aircraft T.A.S. to the local speed of sound, the aircraft T.A.S. must be reduced. If an aircraft has climbed from sea level at a constant speed of ·7M the T.A.S. will automatically be adjusted as height is gained.

27. **The Relationship Between Mach Number and I.A.S.**

(*a*) In the example quoted in the previous paragraph the following data were given :—

T.A.S. (sea level) = 463 knots = ·7M
T.A.S. (40,000 ft.) = 400 knots = ·7M

the temperature conditions being standard atmosphere.

The corresponding approximate rectified air speeds, not corrected for C.E., are :—

R.A.S. (sea level) = 464 knots = ·7M
R.A.S. (40,000 ft.) = 210 knots = ·7M

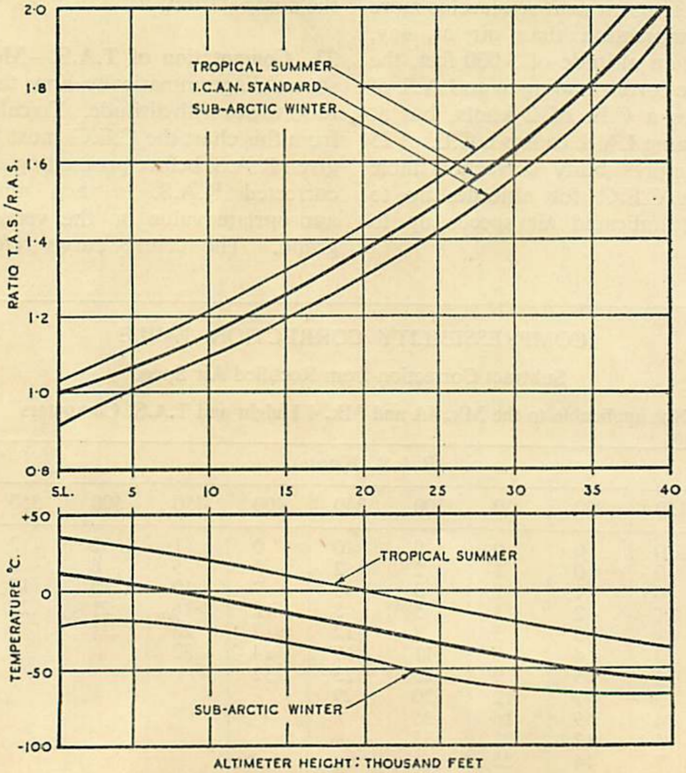


Fig. 1. Graphical Calculation of T.A.S.

From these figures it can be seen that if for aerodynamic reasons the aircraft speed had to be limited to ·7M, this would mean that the I.A.S. would have to be progressively reduced during a climb from sea level in order to observe the limitation. The machmeter simplifies the problem, for all the pilot need do is to maintain the same I.M.N. and by so doing automatically decrease the I.A.S. as height is gained.

(*b*) Machmeters are subject to P.E., since they operate from the same total pressure and static sources as the A.S.I., *i.e.* they show indicated mach numbers. The relationship between true and indicated mach numbers (T.M.N. and I.M.N.) is not the same as between T.A.S. and I.A.S. This is because the machmeter has an altitude-compensating device which allows for compressibility/density errors. In some aircraft the P.E. effect is small over the operating range of mach numbers, and so the difference between T.M.N. and I.M.N. is also small. On some high-speed aircraft, however, the error may become large at high mach numbers ; for such cases Pilots' Notes detail the machmeter P.E.C. The machmeter is also subject to small instrument errors (which are detailed in Part 2, "Flight, Engine, and Ancillary Instruments").

Effect of Speed on Temperature Measurement

28. Effect of Speed on Thermometer Readings.

(*a*) Computing the T.A.S. in flight may entail the use of thermometers in the aircraft. The heat-sensitive parts of the thermometer are necessarily exposed to the free air stream moving past the aircraft. Air which impinges on these parts at high speed is brought to rest, or partially to rest, causing the air to compress and undergo adiabatic heating.

(*b*) The free air thermometer therefore indicates too high a temperature at a given stabilized T.A.S. The indicated temperature should therefore be corrected in accordance with the thermometer calibration card, if fitted. If no such card is carried an approximate correction to deduct from the indicated temperature (°C.) can be obtained from the expression :

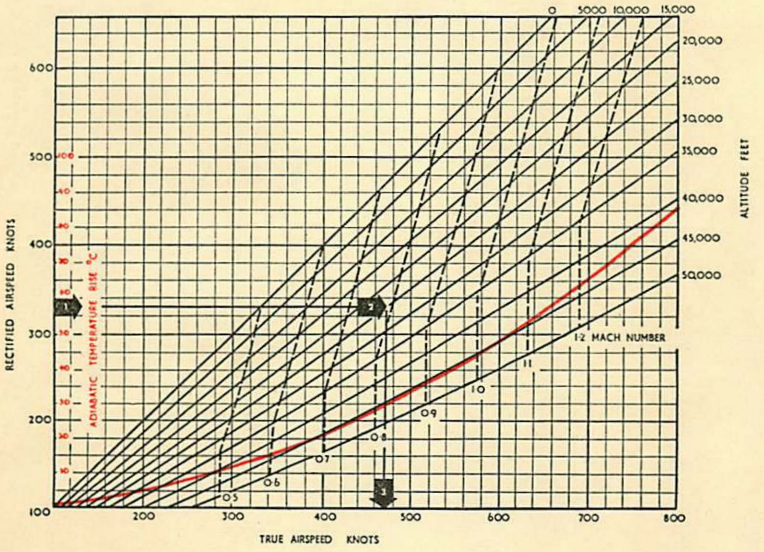
$$\left(\frac{\text{T.A.S. (kts.)} \times 1{\cdot}15}{100}\right)^2 \text{ or } \left(\frac{\text{T.A.S. (kts.)}}{86{\cdot}8}\right)^2$$

The T.A.S. used should be to the nearest 50 knots *above* the estimated T.A.S., *e.g.* at an estimated T.A.S. of 460 knots deduct

$$\left(\frac{500}{86{\cdot}8}\right)^2 = 32{\cdot}5\text{°C. approximately.}$$

Relationship Between I.A.S., T.A.S., Mach Number, and Temperature

29. Fig. 2 is a graph relating the I.A.S., T.A.S., mach number, and adiabatic temperature rise. The figures apply to the standard atmosphere but, especially at high altitudes, any differences caused by small variations in temperature would be negligible for practical purposes.



TO USE CHART:
Enter with RAS 1➡ , move horizontally to altitude 2➡ to find Mach No.
To find TAS, drop to vertical index scale of graph 3➡
TAS values from the graph are correct only on a standard day.
Otherwise TAS values will tend to be conservative when corrected free air temperature is higher than standard, and optimistic when corrected free air temperature is lower than standard.
The effect of C.E. is incorporated in this chart and no separate allowance need be made for it.

EXAMPLE:
On a standard day, 330 knots RAS at 25,000 feet is .78 M and 470 knots TAS.

Fig. 2. The Relationship Between I.A.S., T.A.S., Mach Number, and Temperature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