International standard atmosphere - a tool for technological measurement sovereignty in the aerospace industry

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Abstract. When designing aircraft for agriculture, all calculations are carried out for the International Standard Atmosphere (ISA) conditions, which makes it possible to compare the results of calculations and flight tests of several aircraft conducted in different climatic zones by recalculating the test results to the parameters of the International Standard Atmosphere, "placing" all aircraft in the same conditions - ISA conditions. Historically, the materials for the development of international standards in the field of ISA were developed in the USSR and formed the basis of international standards ISO, which in turn became the basis of documents ICAO 7488/3 of the International Civil Aviation Organisation (ICAO) and subsequently became state documents on standardisation identical to international standards ISO. The above works were carried out within the framework of the international technical subcommittee on standardisation ISO/TC 20/SC 6 "standard atmosphere", formed in 1980 as part of the international standardisation body ISO/TC 20/SC 6 "standard atmosphere". Standardisation is the basis for the unity of measurements. In the Russian Federation, the technical committee on standardisation TC 484 "Standard Atmosphere" was established. The developed model of the International Standard Atmosphere allows us to compare the results of calculations and flight tests of several aircrafts conducted in different climatic zones by recalculating the test results to the parameters of the International Standard Atmosphere, "placing" all aircrafts in the same conditions - ISA conditions. With the development of aviation and space technology, the list of atmospheric parameters subject to normalisation and standardisation is expanding.

1 Introduction

The physical processes and phenomena occurring in the atmosphere in their inseparable connection and interaction with the underlying land and sea surface require study. There is such a variety of alternative aerospace vehicle basing zones on the globe, from the Arctic and Antarctic to the tropics and deserts, that their structural and parametric decomposition is required to ensure uniformity of flight performance measurements. For example, altitudes are measured relative to sea level. And it would seem that oceans and seas all communicate,

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but due to different natural phenomena the unity of measurements is not ensured. Sea level is different in different regions. That is why in Russia since Peter the Great times the Kronstadt Footstick, which fixes the zero level of the Baltic Sea, has been accepted as a unified measure. Other countries have their own zero sea levels. For example, in France the Marseilles Footstroke, and the Amsterdam Footstroke (9 feet 5 inches above sea level - Normal null) is used by all the countries of northern Europe. Italy uses the level of the Eurasian lithospheric plate, and Turkey has taken the average level of the Mediterranean Sea for the period 1936 to 1971, measured in the Antalya area, as a starting point. So historically it happened that maritime affairs determined the unity of altitude measurements.

Meteorology, the science of the atmosphere surrounding the globe, has several sections:

1. Synoptic Meteorology - the doctrine of weather and its prediction,
2. Dynamic Meteorology - studies by theoretical methods atmospheric movements and their relations and interactions with thermodynamic processes in the atmosphere,
3. Climatology - studies the climate,
4. Physics of the upper atmosphere - studies the composition, structure and processes at altitudes above 100 kilometres.

Based on these sections, aviation metrology studies flight conditions that depend on the following parameters: pressure, air temperature and humidity, wind direction and velocity, cloud cover, precipitation, visibility and atmospheric phenomena (thunderstorms, hurricanes, tornadoes, fog, blizzards and dust storms). An important factor in meteorology is the basing condition (surface of runways and taxiways of the aerodrome).

Therefore, it is necessary to take into account and analyse the meteorological situation when designing and operating aircraft. And solving the inverse problem to form the appearance of aircraft from the conditions of their operation, taking into account the natural and artificial environment of operation.

2 Standard atmosphere model

The study of the atmosphere and the phenomena occurring in it has been carried out for several centuries, but it concerns the lower layers [1-4]. With the development of aviation and rocket engineering, the study became systematic and comprehensive. At present, atmospheric research methods are divided into direct and indirect methods. Direct methods:

- meteorological observations on the ground,
- probes (air composition, wind, pressure, temperature and humidity at altitudes from 0-40km),
- aeroplanes (air composition, wind, pressure, temperature and humidity at altitudes from 0-28km),
- satellites (air composition and density, pressure, temperature and solar spectrum at altitudes above 300km).

Indirect methods:

- observation of silvery (wind at altitudes from 80-90 km) and nacreous (wind and humidity at altitudes 22-27 km) clouds,
- anomalous sound propagation (temperature, density, pressure, wind and humidity at altitudes 22-27 km),
- meteor trails (temperature, density, pressure, wind and humidity at altitudes 50-200 km),
- spotlight method (density and temperature at altitudes from 10-65 km),
- ultraviolet radiation spectral studies (20 to 70 km), Night sky studies (60-70 km), Polar aurorae (80-1100 km),
- theoretical studies (over 800 km),
- radiometric methods (air composition, temperature, electrical properties at altitudes from 80 to 800km).

The natural external environment for modern aerial vehicles is the Earth's atmosphere (from Greek atmos - vapour and sphere) and near-Earth space. Atmosphere is considered to be the area around the Earth in which the gas (air) medium rotates together with the Earth as a whole.

The conditional averaged model of the standard atmosphere is accepted by international agreements is the mean annual and mid-latitude state. Why. For a number of engineering calculations of aircraft flight characteristics, for the purpose of their comparability (for example, when calculating lift and drag, for calibration of various aeronautical instruments, in particular altimeters).

The atmosphere consists of air, which is a mixture of gases. Air is a very unstable and unstable medium. Change of basic air parameters (pressure, density, temperature) by altitude, unequal distribution of solar radiation on the globe, changing both by season and during the day, vertical movements of air lead to the fact that depending on the height above the ground, geographical location and other factors, the chemical composition of air, its electrical characteristics are very different.

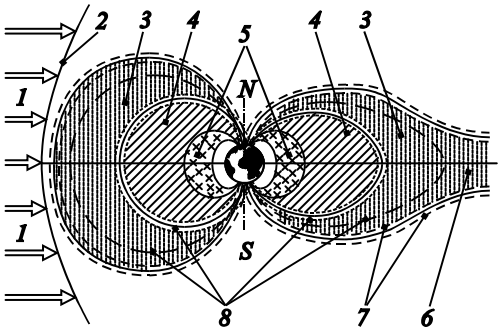

Fig. 1. The Earth's magnetosphere and radiation belts. In the plane of the figure, the Sun and the Earth's poles **N** and **S** [5]

Long-term studies of the Earth's atmosphere by instruments raised to various heights by stratostats, balloon probes, aeroplanes and artificial satellites have made it possible to establish that up to heights of about 80 km the following volumetric composition of dry air can be accepted with a degree of accuracy sufficient for practical calculations: nitrogen - 78%, oxygen - 21%, carbon dioxide and other gases - 1%.

The layer of the atmosphere up to heights of 80-100 km, in which the chemical composition of the air does not change with altitude, is called the homosphere (from Greek homos - equal, the same). Above, in the heterosphere (from Greek heteros - other), with increasing altitude, the chemical composition of the atmosphere changes. Up to heights of 400-600 km the nitrogen-oxygen composition of the atmosphere is preserved, but starting from heights of 110-120 km almost all oxygen is in the atomic state, atomic nitrogen also appears. Further, up to a height of about 1600 km, the atmosphere is dominated by helium, and from heights of about 3000 km and above - hydrogen. So gradually the Earth's atmosphere passes into interstellar gas, consisting of about 76 % of hydrogen and 23 % of helium by mass. Changes in the chemical composition of the atmosphere are caused by dissociation and ionisation processes due to the action of cosmic radiation and solar radiation.

In terms of electrical characteristics in the atmosphere, the neutrosphere, extending to a height of about 60 km, in which air particles have practically no electrical charge (neutral), and the ionosphere, in which gases are in an ionised state (containing free electrons and positively charged ions) and which extends to the boundary of the Earth's magnetosphere 2 (Fig. 1), defined by the equality of the pressure of the Earth's magnetic field (geomagnetic field) and the dynamic pressure of the solar wind 1 (ionised gas flowing out of the Sun).

The magnetosphere includes the inner closed dipole region of the geomagnetic field 8, acting as a trap of charged cosmic particles, and the outer region 7, consisting of magnetic force lines "swept" by the solar wind from the day side of the Earth to the night side and forming on the night side of the magnetic plume of the Earth 6. Charged particles (protons, electrons, particles) captured by the geomagnetic field form the Earth's radiation belt. Conventionally, depending on the distribution of captured particles by energy, the radiation belt - the zone of quasi-capture 3 (from Latin "quasi" - as if, like) of solar wind particles) - is divided into an inner belt and an outer belt. The inner belt 5, beginning at altitudes of 300-1500 km and extending to a height of about 10000 km, in which high-energy protons predominate, poses a danger to aircraft crews. In the outer belt 4, extending to a height of about 50000 km, electrons and protons of low energies predominate.

Naturally, the boundaries by which the atmosphere is divided depending on its chemical, electrical, and radiation parameters are blurred; these parameters depend as significantly on the time of year, the level of solar activity, and other factors as do the basic air parameters in the atmosphere [5-18].

3 Basic parameters and properties of air in the atmosphere

Pressure characterises the intensity of the environmental force at a given point [5]:

$$p = \frac{dF}{dS}$$

Here

p - pressure, Pa (1Pa = 1N/m^2);
F - force perpendicular to the surface of the elementary area, N;
S - surface area of the elementary site, m^2.

Density characterises the amount of mass of air contained in a volume unit:

$$\rho = \frac{m}{W}$$

Here

ρ - density, kg/m^3;
m - air mass, kg;
W - air volume, m^3.

Relative density characterises the change in density as a function of height:

$$\Delta = \rho_H / \rho_0 ,$$

where ρ_H and ρ_0 – density at a given altitude and at the level of the World Ocean, respectively. Temperature characterises the state of thermal equilibrium of a system and is a measure of the kinetic energy of molecules. Absolute temperature T (Kelvin scale) is related to temperature *t* (Celsius scale) by the ratio

$$T = 273+t.$$

The Kelvin scale is named after the English physicist W. Thomson, who received the title of Baron Kelvin for his scientific merits; the Celsius scale is named after the Swedish physicist A. Celsius.

The laws for an ideal gas known from elementary physics describe well the properties of air in the atmosphere, so we can relate the air parameters by the equation of state of the gas (Mendeleev-Clapeyron equation):

$$pW = \frac{m}{M}RT$$

Here

p - pressure;
W - air volume;
m - air mass;
M - molar mass of air (mass of air taken in an amount of one mol);
R - universal gas constant,
R ≈ 8.31 J/(mol·K);
T - absolute temperature.

The equation of state of a gas is named after the Russian chemist D. I. Mendeleev and the French physicist and engineer B. Clapeyron. The gas constant can be expressed in terms of the specific heat capacity of air:

$$R = c_p - c_v = c_v(\kappa - 1),$$

Here

c_p - specific heat capacity at constant pressure (for air $c_p \approx 1000$ J/(kg·K));
c_v - specific heat at constant volume (for air $c_v \approx 716$ J/(kg·K));
κ - heat capacity ratio c_p / c_v.

Thus, for air κ ≈ 1.41.

It should be recalled that heat capacity is defined by the amount of heat that must be brought to a given volume of air (or removed from it) in order to raise (or lower) its temperature by 1K.

Compressibility characterises the property of air to change its volume and density with changes in pressure and temperature [19-45].

Elasticity characterises the property of air to return to its initial state after the cessation of the forces that caused its deformation. Naturally, for air such deformation can be only the deformation of its volume under all-round compression.

The property of compressibility and elasticity of air is manifested in the fact that any perturbation in it, i.e. local compression (local increase in pressure and density of air), propagates in the form of very small perturbations - pressure and density fluctuations. These fluctuations occur at sonic frequencies and propagate as waves at the velocity of sound. Thus, the velocity of sound (the velocity of propagation of a sound wave in air) characterises the elasticity and compressibility of air.

The velocity of a wave can be determined by the relation

$$a^2 = \frac{dp}{d\rho},$$

Here

p - wave pressure;
ρ - propagating wave density.

Approximately the process of sound wave propagation can be considered as adiabatic, i.e. one in which the propagating wave does not receive heat from outside and does not give it to the surrounding medium. In this case $\frac{dp}{d\rho} = k\frac{p}{\rho}$ and the velocity of sound will be expressed as $a = \sqrt{k\frac{p}{\rho}}$

Determining from the gas equation of state the pressure through density and substituting the values of the air parameters into the equation for the velocity of sound, we obtain a ≈ $20\sqrt{T}$,

Here

a - sonic velocity, m/s;

T - air temperature, K.

Number M (Mach number, after the Austrian scientist E. Mach) - characteristic of air (gas) flow, equal to the ratio of velocity V air flow (velocity of a body in the air) to the velocity of sound a at a given flow point:

$$M = \frac{V}{a}$$

Viscosity (or internal friction) characterises the property of air to resist the relative movement of its particles, as well as the movement of a solid body in air. The cause of viscosity is the interaction of molecules in their chaotic motion [46-57].

Viscosity manifests itself in the fact that when neighbouring layers of air shear, a force arises F (friction force) that resists shear:

$$F = \mu \frac{\mathrm{dV}}{\mathrm{dy}} S$$

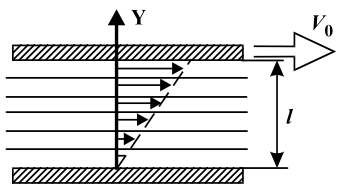

Fig. 2. Towards an explanation of the concept of air viscosity

Here

μ - proportionality coefficient, called dynamic viscosity coefficient, N ·s/m^2 (Pa·s);

$\frac{\mathrm{dV}}{\mathrm{dy}}$ - is the gradient of layer velocity change in the direction perpendicular to the air velocity, 1/s;

S - area of the layer for which the force is calculated, m^2;

F - force, N.

Let us imagine two plates with a layer of viscous air between them (Fig. 3, 4).

If one of the plates starts to move with velocity V_0, then the layer of air immediately adjacent to the plate will have the same velocity. Each subsequent layer will have a lower velocity due to viscosity (friction between the layers). The layer adjacent to the stationary plate will remain stationary. In this case, the force F, that must be applied to the plate to make it move at a velocity of V_0 determined as $F = \mu \frac{V_0}{l} S$ where $\frac{V_0}{l}$ is gradient of layer velocity change.

Kinematic viscosity coefficient - ratio of dynamic viscosity coefficient to medium density

$$: \nu = \mu / \rho.$$

4 International standard atmosphere (ISA)

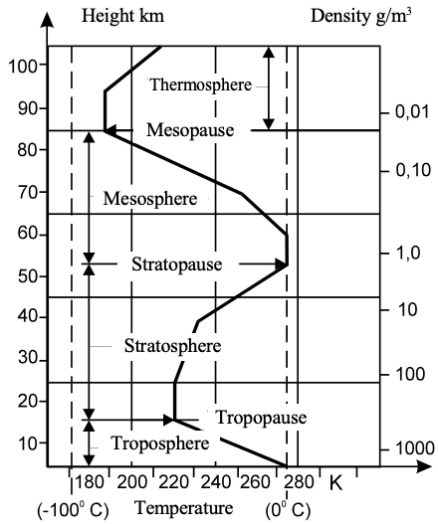

Fig. 3. ISA parameters [6]

The need to compare the results of flight tests of aircraft [7-10] in different conditions led to the creation of a mathematical model of the conditional atmosphere. In accordance with this model, the atmosphere is divided by height into several layers, within which the temperature varies according to a certain law that coincides quite closely with the mean annual values at midlatitudes in summertime (Fig. 3). These are the troposphere (from Greek tropos - turn, change), stratosphere (from Latin stratum - layer), mesosphere (from Greek mesos - middle, intermediate), thermosphere (from Greek terme - heat, heat), exosphere (from Greek exo - outside, out).

Comparatively thin layers of the atmosphere, the thickness of which is measured in tens and hundreds of metres, separating the main layers of the atmosphere from each other, are called tropopause, stratopause, mesopause, respectively.

The international standard atmosphere, unified for all states, is a conditional atmosphere in which the pressure distribution by height in the gravity field is obtained under certain assumptions about the vertical temperature distribution from the barometric formula

$$p_n = p_0 \exp(-\frac{Mgh}{RT})$$

Here

- p_n - altitude pressure;
- p_0 - sea level pressure;
- M - gas molar mass;
- g - free-fall acceleration;
- R - universal gas constant;
- T - temperature;
- h - Boltzmann constant (after the Austrian physicist L. Boltzmann).

ISA takes the level of the World Ocean as the starting point of height under the following normal conditions: acceleration of free fall $\mathbf{g_0}$=9.807 m/s^2; pressure $\mathbf{p_0}$=101325 Pa (760 mmHg); density $\boldsymbol{\rho_0}$=1.2257 kg/m^3 ; temperature $\mathbf{T_0}$=288 K ($\mathbf{t_0}$ = 15°C); sound velocity $\mathbf{a_0}$ = 340 m/s.

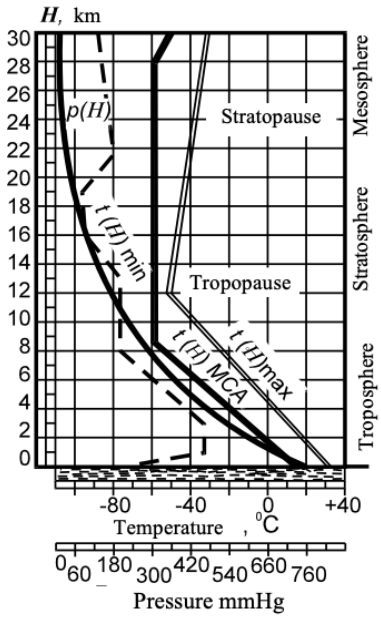

Fig. 4. ISA parameters for low altitudes [6]

Detailed tables of standard atmosphere parameters are given in the literature. Special mathematical computer software has standard programmes that allow us to calculate ISA parameters.

ISA parameters (change of air temperature and pressure) for low altitudes at which helicopters and aeroplanes fly are given in Fig. 4.

The data on the distribution of average annual temperature values are given here as well: $t(H)_{max}$ and $t(H)_{min}$. In the first approximation for the troposphere (H = 0÷11 km) may be as:

$$t_H = 15 - 6.5H;\ a_H = a_0 - \frac{H}{0.25};\ \rho_H = \rho_0 \frac{20-H}{20+H},$$

Here

- t_H - altitude air temperature H, °C;
- a_H - sonic velocity at altitude H, m/s;
- a_0 - velocity of sound at the level of the World Ocean, m/s;
- ρ_H - air density at altitude H, kg/m^3;
- ρ_0 - air density at sea level, kg/m^3;
- H - design altitude, km.

In the stratosphere (up to an altitude of 20 km) to a first approximation:

$$t_H = \text{const} = -56.5°C;\ a_H = \text{const} = 295.1 \text{ m/s};\ \rho_H = \rho_{11}\, e^{-\frac{H-11}{6.318}},$$

Here

- ρ_{11} - air density at 11 km altitude, kg/m^3;
- ρ_H - air density at design altitude H, kg/m^3;
- H - design altitude, km.

All aircraft design calculations are carried out for ISA conditions, which allows comparing the results of calculations and flight tests of several aircraft carried out in different climatic zones by recalculating the test results to the parameters of the international standard atmosphere, "placing" all aircraft in the same ISA conditions [11-14].

5 Conclusions

The developed model of the international standard atmosphere makes it possible to compare the results of calculations and flight tests of several aircraft conducted in different climatic zones by recalculating the test results to the parameters of the international standard atmosphere, "placing" all aircraft in the same ISA conditions.

With the development of aviation and space technology, the list of atmospheric parameters subject to normalisation and standardisation is expanding.

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