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ORIGINAL PAPER

Theoretical analysis of decompression tolerance based on a simulated depressurisation model of an aircraft's pressurised cabin

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Abstract

The method presented in the article is based on a complex simulation model of gas-dynamic processes that take place in sectioned cabins during depressurization. This model allows the theoretical calculation of decompression parameters (decompression time, cabin pressure, gas leakage from the cabin) depending on flight parameters and design features of the aircraft pressurised cabin (height, cabin volume, defect area, etc.) and determine the interdependence of pressure control parameters in critical operating modes. In computational experiments simulating decompression during depressurisation, the rate of cabin pressure drop as a function of the defect area, residual overpressure, decompression time, values of drops between compartment sections and mass flow rate during pressure changes; safe descent height and other parameters were determined. On the basis of computational experiments, a methodology for assessing the portability of decompression was developed, taking into account different levels of impact tolerance, allowing for a rational choice of hermetic and gas dynamic parameters of the cabin, as well as flight performance characteristics, taking into account the possible decompression of the cabin in flight or, conversely, with the specified parameters of the cabin and flight data at the design stage of the aircraft to assess the degree of danger in case of depressurization and to provide in advance a set of security measures. The transition for decompression safety analysis along the Chadov V. I. curve has advantages since it is applicable for various types of aircraft from spacecraft to aircraft and for various atmospheres with different combinations of pressures and concentrations.

Keywords Depressurisation · Leakage rate · Decompression · Computational experiments · Simulation model · Equivalent areas · Altitude sickness · Hypoxia · Barotrauma

1 Introduction

A pressurized cabin (PC) of various types of aircraft from spaceships to aircraft, in which the parameters of the internal environment are regulated to ensure not only the preservation of life, but also the maintenance of operability at the required level are the main means of protecting a person from the effects of the external environment and maintaining the necessary physiological and hygienic conditions of normal life and performance in conditions high-altitude flight. Depressurization can occur either due to abnormal opening of exhaust valves, or due to non-inclusion of air intake after take-off, incomplete closing of doors and hatches of the aircraft; failure of the automatic pressure control system (APCS), explosions inside and outside the aircraft, for example, breakdown of the passenger compartment by a metal fragment of an exploded engine, separation of parts of the air vessel due to overloads. Usually, in works dealing with aircraft cockpit decompression (AC), sudden depressurisation from a physiological point of view is considered as a sum of dangerous factors for the human body: reduction of oxygen partial pressure, danger of relative gas expansion, the phenomenon of decompression at high altitudes.

The development of altitude decompression illness is regarded as one of the most serious problems arising from decompression. With a significant increase in flight time, without adequate means and protection, any decompression, whether slow or explosive, will have one outcome: human death [1].

The need for a methodology to assess human tolerance to decompression in forced PC decompression is determined by the fact that the existing means of regulating air pressure in the PC do not fully take into account: technical capabilities

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and limitations of existing means of development and regulation of air parameters in the aircraft cabin; physiological and hygienic effects affecting the crew during their activities in standard and emergency situations; potential technical capabilities, use of other means and ways of optimising the crew's activity conditions during manoeuvring (high manoeuvring) and high altitude (stratospheric) flights in standard and emergency conditions.

The sources of air supplied to the PC are engines of various types and operating principles. Their main purpose is to ensure their own operation, and the function of air supply to the cabin and technical compartments, is auxiliary. At the same time, the existing limitations of technical means of pressure control in PC are due to the traditional tasks of regulation, aimed at maintaining the specified parameters of the pressure gradient, rather than pressure level constancy, taking into account the physiological needs of the body. The issues of extending the functionality of aircraft engines in the interests of optimising microclimatic conditions in the cockpit for the crew and passengers are currently not considered.

Since the main and effective means of protection against decompression and pressure drop is the APCS, to solve the above tasks, it is necessary to develop a methodical and algorithmic apparatus of APCS analysis, allowing at the design stage to calculate optimal conditions ensuring comfortable conditions and pilot protection from adverse factors of high-altitude flight [2]. Thus, the aim of the work was to justify and develop a methodology to assess the pilot's decompression tolerance at different defect values based on a comprehensive simulation model of gas dynamic processes. This methodology will make it possible to theoretically estimate the value of standby time depending on the level of exposure tolerance.

In order to achieve our goal, we had to solve the following tasks:

1. Based on existing approaches, form a decompression decompression simulation model to account for the effect of decompression on the body depending on flight parameters, PC characteristics and APCS operation modes.
2. Conduct computational experiments simulating cabin depressurization at different values of leakage factor. In the course of computational experiments to determine the time of PC decompression, the value of drops between PC compartment-sections when changing pressure, the value of mass feed when changing pressure in the PC, the value of safe descent height.
3. On the basis of computational experiments to develop a methodology for assessing human decompression tolerance, taking into account different levels of exposure tolerance.

2 Materials and methods

2.1 Simulation model of pressurised cabin decompression during depressurization

Flight safety directly depends on the condition of the environment in the pressurised cabin. The problem of ensuring safety during depressurisation must be considered as a set of measures providing both physiological and strength protection to ensure flight safety and preservation of crew life, and, therefore, the study of this problem must be comprehensive. It is the concept of an integrated consideration of the whole problem, both from physiological and technical points of view, and the identification of possible means and measures to ensure safety, that forms the basis of the study.

To normalise the pressure in the PC, APCS is used, which maintains the pressure by supercharging with atmospheric air from the aircraft engine compressor and venting excess air into the atmosphere. Depressurisation occurs in the course of leakage of gases from the pressurised cabin, which can be caused by leaks in the casing, wear of gaskets, getting damaged during the flight, equipment failure. At the same time, the existing limitations of technical means of development and do not allow to avoid gas outflow through the smallest leaks do not allow creating fully hermetic systems. Therefore, it is impossible to refuse APCS, one of the basic parameters of which is mass delivery equal to mass flow rate of gas including that flowing out through the leakage.

In these conditions the problem of pressure regulation in PC is not only actual, but also one of priority at development of new aviation equipment and individual protection means. In practice of AC design, a wide range of various safety tasks have to be solved in case of accidental or deliberate depressurisation of the cabin in flight. First and foremost, they should include tasks of the most important practical importance, namely: determination of possible pressure drops and pressure equalisation between PC compartments in case of pressure changes and/or in case of depressurization of one of them; determination of mass flow rate in case of sudden depressurisation and/or pressure change in PCs; determination of PC decompression time; determination of required speed of aircraft emergency descent to a safe altitude in case of sudden depressurization.

To solve the complex problem of developing a simulation model of decompression during PC decompression, three interrelated and interdependent subtasks must be solved: to analyse existing approaches to simulating decompression during cabin depressurisation; to develop a decompression model during depressurisation; to form a model of the body's respiratory system.

The development of accurate models to calculate pressure changes in aircraft compartments under pressure is of great interest. One of the pioneering work in the field of express—decompression analysis is the paper by Haber and Clamann [3]. They clearly analysed the complexity of the phenomenon and developed a zero-dimensional polytropic model. In addition to developing theoretical polytropic decompression models, the authors also carried out experimental studies, which established values of the mean polytropic index $n = 1.16$ averaged over 75 decompression experiments. The authors also provided an analytical expression for the decompression time, which includes supercritical and subcritical modes, but requires a separate diagram to calculate the pressure ratio. To this day, Haber and Clamann's theory is considered to be fundamental in aircraft decompression analysis.

The first published paper on decompression in a spacecraft cabin is by Demetriades [4]. The author investigated isentropic decompression of a pressure cabin in vacuum. He defined the relationship between initial and final pressure as a function of decompression time. However, he did not consider any repressurization, which is the most common countermeasure against decompression in modern spacecraft, and the output did not include a correction for the flow coefficient. He investigated the dynamics of decompression and developed countermeasures that ensured the safety of the first human spaceflight.

Mavriplis [5] published an extensive study of the failure of pressurised cabins, both aircraft and spacecraft. He developed isothermal, isentropic and polytropic models and gave various numerical examples for single-, double- and triple-compartment cabins. He formulated equations for the calculation of air outflow, decompression time, the necessary cabin air inflow to increase the decompression time and the pressure–time relationship of an individual compartment.

Langley [6] suggested the use of compartmentalization of aircraft using experience from the design of seagoing vessels. He suggested that by sealing the various compartments, decompression should be prevented from spreading throughout the aircraft.

Yakovlenko [7] calculated overpressure in human lungs and danger of dysbarism during space cabin decompression. The main feature of his mathematical model was the simultaneous calculation of the amount of air expelled from the human lungs and lung expansion due to cabin decompression, which led to agreement of experimental results with theoretical studies.

Schroll and Tibbals [8] presented a model with concentrated parameters and an associated computer program with a graphical user interface to simulate a rapid decompression of an aircraft cabin. Their model is based on a simple isentropic outflow and changes in the cabin air state. Their main purpose was to estimate the amount of emergency oxygen supply, taking into account descent to safe altitudes. They did not take into account the emergency descent characteristics of the aircraft, the multi-sectionality of the cabin and the dynamics of the ventilation system.

In the works mentioned above, the authors did not consider active vents, which are panels that open in time when the design pressure difference between the two compartments is reached. These devices facilitate the air flow and redistribute the pressure, thus limiting the pressure forces on the structures.

An article by Breard et al. [9] is devoted to solving the cockpit security door problems. The authors used a commercial 3D computational fluid dynamics (CFD) code to calculate the external velocity and pressure distribution around the aircraft cockpit, as well as the internal pressure distribution in the cockpit caused by porthole damage. The CFD uses Navier–Stokes equations to determine turbulence values. Breard et al. simulated the collapse of the porthole, during a rapid depressurization, and calculated the force acting on the baffle plates, the pressure drop and the dynamics of cabin decompression.

Daidzic and Simones [10] developed zero-dimensional isothermal and isentropic models of cabin decompression with and without a security door. In their study, two hinged panels in the security door were modelled to account for the pressure equalisation dynamics in the case of decompression. Their work proposed various analytical solutions along with formulas for estimating decompression times. However, the passive and active ventilation systems providing communication between compartments were considered as one and only single- and two-compartment systems were analysed.

Pratt [11] examined the dynamics of passive and active, vented blowout preventer panels and hinged doors between different airtight aircraft compartments in the case of rapid decompression. He developed an isentropic model and emphasized the importance of considering the weight of the panels when estimating pressure drops between compartments. However, in his work he considered only the pre-critical regime, which could be of interest for operational altitudes below about 7300 m.

Pagani and Carrera [12] focus on the modelling of active vents within an isentropic model of airborne and spacecraft decompression. The theoretical modelling of this phenomenon for both subcritical and supercritical regimes is presented. Models of both hinged and translational blowdown panels, including inertial effects, are presented. Subsequently, a general numerical procedure for solving coupled differential equations for multi-section aircraft is developed.

The analysis of existing approaches to simulation of decompression during depressurization has shown that the process of gas flow through a hole from a limited vessel is not steady in time and should be considered as a non-stationary process, caused primarily by a continuous change of gas state, as well as by a wave nature of the phenomenon in question.

Nevertheless, the dependence of the gas flow through the orifice can be well approximated by formulas developed within the theory of quasi-steady-state processes. The comparison of results of calculations of mass and mass flow in time according to wave theory and quasi-steady-state theory [13] has shown that the time dependence of mass at a sound gas flow from a vessel of finite dimensions can be well approximated by applying the provisions of quasi-steady-state theory with the use of correction factors (flow coefficient). This makes it possible to replace the non-stationary process in question with an imaginary stationary one.

Mathematical models of air outflow processes from the compartment are presented in papers [13–17]. In these publications, approaches of Olizarov, Ilyushin can be distinguished. [14], Akopov [15] and Bykov et al. [16, 17] based on positions of quasi-stationary theory. In these works, the following main mathematical laws of outflow from PC were obtained: empirical formulas for determination of gas flow rate and pressure in subcritical and overcritical flow modes were derived; approximate formulas for calculation of gas condensate decompression time at constant pressure in the atmosphere and isothermal change of parameters are derived.

In the work of Bykov et al. [16] presents dimensionless dependences of the PC decompression for the isothermal state in the case of flow in the medium with constant pressure, which are convenient for preliminary calculations.

In all the above papers, except Ivlentyev and Bykov et al. [17], the cabin was considered as one pressurised volume, and the outflow process took place in an environment with constant parameters, i.e. in the assumption that the flight altitude, during the depressurization process, does not change. However, the PCs of modern aircraft can be divided by partitions into separate communicating sections or pressurised compartments. Besides, in case of unforeseen cabin depressurization at high altitude, the crew will naturally take emergency measures to reduce the aircraft to a safe altitude and the leakage process in these conditions will proceed with variable (increasing) external backpressure.

In qualitative comparison the approach of Olizarov, Ilyushin is the most adequate, in calculation by which the pressure in the modelling end-point is 42 mm Hg, which corresponds to the simulated altitude of 20 km.

When calculated using the approaches of Akopov and Bykov, Egorov, Tarasov, respectively 38 mmHg and 78 mmHg, which distorts the real process of gas outflow, since the pressure at the endpoint cannot be higher or lower than the atmospheric pressure. This leads to the fact that the outflow process continues at equal pressures in the cabin and in the atmosphere. This contradicts the physical sense of the process. Therefore, we took the approach of Olizarov and Ilyushin as the basic one.

In developing a simulation model of pressurised cabin decompression during depressurization, special attention was paid to investigating and solving the problem of air outflow from the PC in conditions of variable external backpressure, i.e. under conditions of emergency descent to a safe altitude during sudden in-flight cabin decompression. The main task of the theory of gas outflow is to establish the relationship between the flow rate and gas parameters of the vessel and the medium into which the outflow occurs. An aircraft can be thought of as a vessel containing an atmosphere, which is matter in a gaseous state. Gas molecules, being at a considerable distance from each other, are randomly moving inside the vessel, colliding with each other and continuously bombarding the walls, thus putting pressure on them. The sudden disturbance of the cabin walls entails rapid dispersion of the gases inside the cabin.

The use of quasi-stationarity hypothesis in engineering problem statement is fully justified and necessary because it simplifies the solution and contributes to achieving the goal while maintaining sufficient accuracy of the practical result [13]. Proceeding from this, at research the following assumptions are accepted: thermodynamic process of AC depressurization was considered as a sequence of quasi-steady regimes; specific heat capacities of air were considered constant during the whole depressurization time; air was assumed to be an ideal gas; adiabatic change of gas parameters in the hole did not influence the character of gas state change in the volume; at each moment of time in PC a uniform distribution of pressure and temperature was realised; gas movement in PC volume and its local acceleration in the depressurization hole was not considered, i.e. the state of air in the cabin was considered to be retarded; PC decompression process was considered in terms of thermodynamics of a body of variable mass; alveoli at any time had the same gas mixture composition and were equally ventilated and perfused.

The main factors determining the rate and extent of any decompression are cabin volume, orifice area; and pressure differential. The amount of gas escaping from the cabin through a leakage depends on the sum of the areas of all the orifices through which the leakage occurs [14]. To calculate the leakage, the real cabin was replaced by a model with only one air outlet opening $\mathrm{S_y} = \sum \mathrm{S_i}$. Thus, the PC can be schematically represented as a sealed volume with an opening of constant cross-section, through which air flows out, and the flow rate is equal to the leakage. Using such a model, it is possible to determine the dependence of pressure in the cabin on the time during which decompression takes place.

Four areas were considered: 1—atmosphere, 2—first compartment—pressurised cabin, 3—second technical compartment, 4—human lungs.

The formalised description of the depressurisation process has been supplemented with:

conditions defining the atmospheric parameters, allowing their influence on the character of gas outflow to be taken into account when changing the altitude [14]:

$$t_h = t_0 + \alpha \cdot h,\ \ p_h = p_0 \cdot \left(1 - \frac{h}{44,\,300}\right)^{1/\alpha \cdot R},$$
$$\rho_h = \rho_0 \cdot \left(1 - \frac{h}{44,\,300}\right)^{\frac{1}{\alpha \cdot R} - 1},\ \text{at}\ h < 11,\,000\ \text{m}, \quad (1)$$
$$t_h = -56.5^\circ\text{C},\ \ p_h = 169.4 \cdot \mathrm{e}^{-\frac{h-1100}{6340}},$$
$$\rho_h = 0.3636 \cdot \mathrm{e}^{-\frac{h-1100}{6340}},\ \text{at}\ h > 11,\,000\ \text{m}$$

by introducing a variable flow coefficient to improve calculation accuracy [18]:

$$\begin{cases} k_{\text{flow}} = 0.55,\ \text{at}\ \ k_{\text{flow}} \le 0.55 \\ k_{\text{flow}} = -0.2785 \cdot \left(\frac{p(j-1)}{p(j)}\right)^2 - 0.065 \cdot \left(\frac{p(j-1)}{p(j)}\right) \\ +0.852\text{at}\ \ 0.55 \le k_{\text{flow}} \le 0.95 \\ k_{\text{flow}} = 0.95,\ \text{at}\ \ k_{\text{flow}} \ge 0.95 \end{cases} \quad (2)$$

where $j = \{1, 2, 3, 4\}$ is the sequence number of the site.

- The ratios for determining decompression times presented in an article by Tarasov V.V. [19];
- introducing into Eqs. (7) and (9) to determine the value of pressures change of mass feed ($G_{\text{regulation}}$):

$$G_{\text{reg}}(j) = k_{\text{prop}} \cdot \frac{V_k(j) \cdot \left(p_{\text{reg}} - p_k(\text{j})\right)}{R \cdot T_k(j)}, \quad (3)$$

where V_k is the cabin volume, m^3, $p_{regulation}$ is the target pressure, Pa, p_k is the cabin pressure, Pa, T_k is the cabin temperature, °K, R is the gas constant of air.

- The introduction of a second technical compartment, as consecutive gas leakage from a multi-sectional compartment affects the gas flow regime and the equipment in the technical compartment is subject to increased requirements for thermal protection;
- introduction of a new component—human lungs.

The main variables determining the state of the gaseous environment in a confined space are pressure, volume and temperature, density and humidity. The law of pressure variation in the pressurised cabin was as follows:

$$p_{\text{reg}}(j) = p_h + 0.5465 \cdot (p_0 - p_h). \quad (4)$$

The equivalent leakage area was determined using the formula:

$$f_e(j) = k_{\text{flow}}(j) \cdot S_{y.} \quad (5)$$

Air temperature in the PC [14]:

$$T_k(j) = T_0 \cdot \left(\frac{p_k(j,\,1)}{p_k(j)}\right)^{\frac{1-n}{n}}. \quad (6)$$

PC of modern aircraft in general case can be represented as several (usually not more than two or three) communicating sections or compartments, each of which is connected to the environment through a pressure regulator valve.

When considering the process of gas outflow from vessels of unlimited capacity, theories have established a certain dependence between the gas flow rate, the area of the passage opening, the parameters of the gas in the cabin and the parameters of the external environment. The magnitude of the leakage determines the rate of change in the pressure of the gas environment in the cabin, which has a well-defined effect on the aircraft crew's vital functions. To quantify the magnitude of the leakage, it is necessary to determine the mode of gas flow through the orifice. The initial equations for the first compartment are as follows:

- in the case of a critical outflow $p(j)/p(j-1) \ge 1.89$:

$$G(j) = \frac{f_e(j) \cdot a \cdot p(j)}{\sqrt{T_{k(j)}}}, \quad (7)$$

$$\frac{\mathrm{d}p(j)}{\mathrm{d}t} = \frac{R \cdot T_k(j)}{V_k(j)} \cdot \left(G\,(j+1) + G_{\text{reg}}\,(j)\right) - \frac{a \cdot R \cdot \sqrt{T_{k(j)}} \cdot p\,(j)}{N_y\,(j)}, \quad (8)$$

where $a = \sqrt{\frac{k}{R} \cdot \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$, $N_y(j) = V_k(j)/f_e(j)$—degree of tightness.

- in the case of a pre-critical expiry $p(j)/p(j-1) \le 1.89$:

$$G\,(j) = \frac{b}{\sqrt{T_k\,(j)}} \cdot f_e\,(j) \cdot p\,(j) \cdot \sqrt{\left(\frac{p\,(j-1)}{p\,(j)}\right)^{\frac{2}{k}} \cdot \left(1 - \left(\frac{p\,(j-1)}{p\,(j)}\right)^{\frac{k-1}{k}}\right)} \quad (9)$$

$$\frac{\mathrm{d}p\,(j)}{\mathrm{d}t} = \frac{R \cdot T_k(j)}{V_k(j)} \cdot \left(G\,(j+1) + \Delta G_{\text{reg}}\,(j)\right) - \frac{b_1 \cdot n \cdot R \cdot \sqrt{T_k^{\text{pre}}\,(j)} \cdot p\,(j)^{\frac{3 \cdot n-1}{2 \cdot n}}}{N_y \cdot p\,(j)^{\text{pre}\,\frac{n-1}{2 \cdot n}}}, \quad (10)$$

where $b = \sqrt{\frac{2}{R} \cdot \left(\frac{k}{k-1}\right)}$, $b_1 = \sqrt{\frac{2 \cdot k}{R \cdot (k-1)}} \cdot \left(\frac{p(j-1)}{p(j)}\right)^{1/k} \cdot \sqrt{1 - \left(\frac{p(j-1)}{p(j)}\right)^{\frac{k-1}{k}}}$.

The smaller the volume of the PC or the larger the opening, the faster the decompression will occur. The length of time for air to leave the cabin while within the atmosphere is significant, due to the decrease in the partial pressure of oxygen in the cabin, leading to the development of hypoxia. Accordingly, the total decompression time was determined by the following summation [14]:

$$t_{\text{dec}} = t_{\text{overc}} + t_{\text{prec}}, \tag{11}$$

where t_{overc} is the time of overcritical expiration; t_{prec} is the pre-critical expiration time.

Decompression time was determined by the following formulas presented in [19]:

$$t^{1}_{\text{overc}}(j) = K_a(j) \cdot \frac{2}{k-1} \cdot \sqrt{\pi_{\text{cr}}^{\frac{k+1}{k}}} \cdot \sqrt{\left(\frac{\pi_0(j)}{\pi_{\text{cr}}}\right)^{\frac{k-1}{k}} - 1}, \quad \text{at} \quad \pi_0(j) > \pi_{\text{cr}}, \tag{12}$$

$$t_{\text{overc}}(j) = t^{1}_{\text{overc}}(j) + K_a(j) \cdot \pi_{\text{cr}}^{0.355 \cdot \frac{2-k}{k}} \cdot \sqrt{\pi_{\text{Kp}}^{\frac{k-1}{k}}}, \quad \text{at} \quad \pi_0(j) = \pi_{\text{cr}}, \tag{13}$$

$$t_{\text{cr}}(j) = K_a(j) \cdot \pi_{\text{cr}}^{0.355 \cdot \frac{2-k}{k}} \cdot \sqrt{\pi_{\text{cr}}^{\frac{k-1}{k}}} \text{ at } \quad \pi_0(j) < \pi_{\text{cr}}, \tag{14}$$

$$t_{\text{pre}}(j) = K_a(j) \cdot \pi_0(j)^{0.145 \cdot \frac{k+1.45}{k}} \cdot \sqrt{\frac{2}{k-1} \cdot \left(\pi_0(j)^{\frac{k-1}{k}} - 1\right)}, \tag{15}$$

where $\pi_0(j) = \frac{p(j,1)}{p(j)}$, $\pi_{\text{cr}} = \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}$, $a_0 = \sqrt{k \cdot R \cdot T_0}$, $K_a(j) = \frac{V_k(j)}{f_e(j) \cdot a_0}$.

A similar system of equations can be constructed for objects consisting of any number of compartments.

When constructing a model of the respiratory system of the body, the model presented in our previous publications [20, 21] was taken as the basic model. In the model of gas transport in the human body, 3 compartments were identified: inhaled; exhaled; alveolar gas mixture. Stresses, concentrations, masses of gases were calculated.

The risk of altitude decompression sickness (DCS) was determined by a formula approximating the safe pressure curve experimentally determined by V.I. Chadov [22]:

$$p^{\text{decom}}_{\text{safe}} = -3.514 \cdot 10^{-6} \cdot p^{3}_{N_2} + 0.005 \cdot p^{2}_{N_2} - 1.624 \cdot p_{N_2} + 336.7834. \tag{16}$$

The transition for decompression safety analysis using the Chadov V. I. curve has advantages because it is applicable for different types of aircraft from spacecraft to aircraft and for different atmospheres with different combinations of pressures and concentrations.

The risk of DCS is currently assessed by the oversaturation ratio, which is the ratio of the partial pressure of nitrogen before decompression to the total pressure after decompression:

$$K_n = \frac{p^{I}_{N2}}{p^{\text{decom}}_{\text{safe}}}. \tag{17}$$

For a terrestrial atmosphere of 760 mmHg, $K_{\text{n}} = 1.6$.

The transition for decompression safety analysis using the V.I. Chadov curve has advantages as it is applicable for different types of aircraft, from spacecraft to aircraft, and for different atmospheres with different combinations of pressures and concentrations.

The safe altitude was determined from the condition:

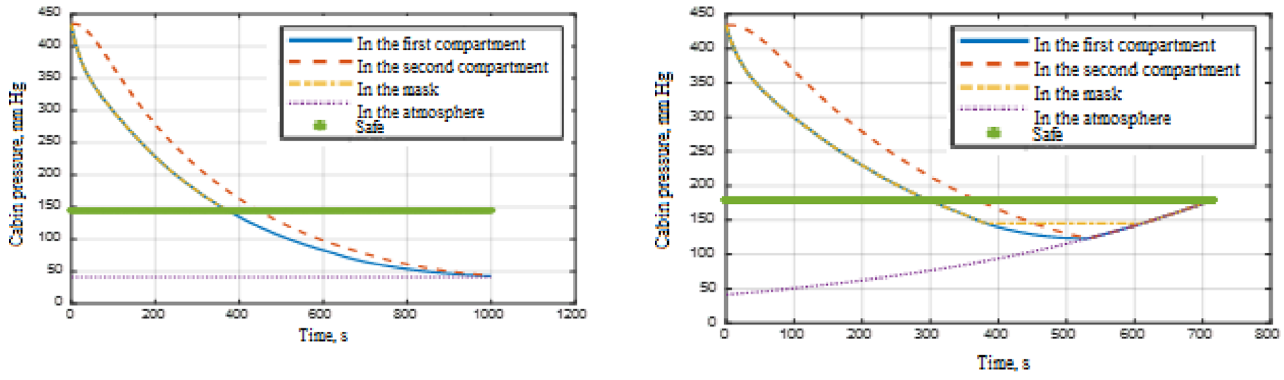
$$\begin{cases} H_{\text{safe}} = 44{,}300 \cdot \left(1 - \frac{p^{\text{decom}}_{\text{safe}}}{p_0}\right)^{1/5.256}, \\ \quad at \quad p^{\text{decom}}_{\text{safe}} \leq 170.19; \\ H_{\text{safe}} = 11{,}000 - 6340 \cdot ln \frac{p^{\text{decom}}_{\text{safe}}}{169.4}. \\ \quad at \quad p^{\text{decom}}_{\text{safe}} \geq 170.19 \end{cases} \tag{18}$$

2.2 Computational experiments to simulate depressurization

Computational experiments determined the pressure drop rates in the PC as a function of the defect area and the required air supply to compensate for these leaks. The depressurisation simulation was carried out with different values of equivalent hole areas at different heights. For this purpose, we selected hole diameters of 5, 10, 15, 20, 25 mm. Since in practice the holes may have different shapes and sizes and there may be several of them, for the convenience of calculation we introduced a leakage coefficient a value inverse to the degree of tightness. This coefficient allows any ratio between the opening area and the cabin volume to be taken into account:

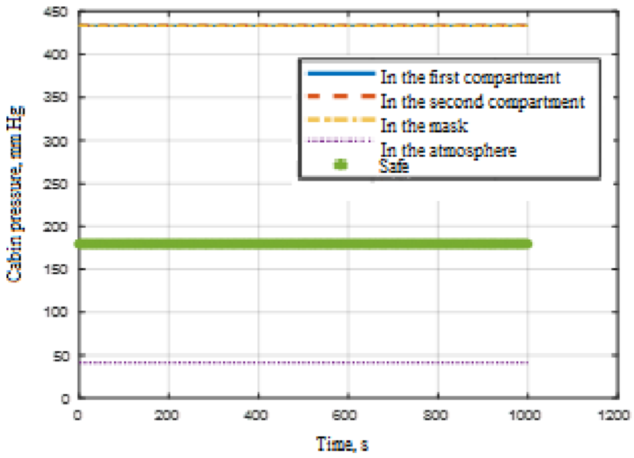
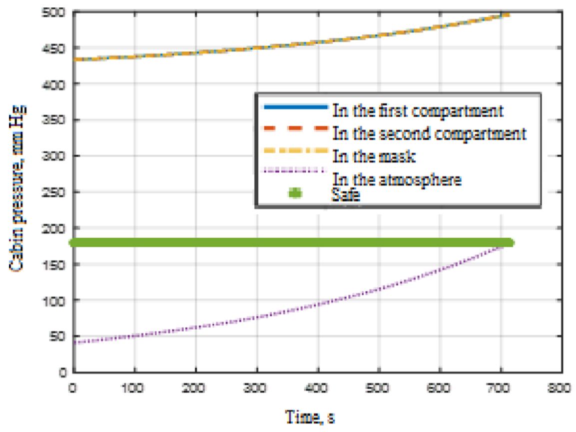
$$k_l = \frac{f_y}{V_k}. \tag{19}$$

The results of calculating the decompression pressure dynamics as a function of decompression time are shown in Fig. 1 at altitude and with descent. On the graph, the horizontal line is an approximation of the experimental safe pressure curve of Chadov V.I. [22]. What is below this line is decompression dangerous, what is above is decompression safe. The resulting calculated curves are qualitatively consistent with



a) flight altitude

b) reduction

c) compensated

d) with reduction and compensation

Fig. 1 Pressure dynamics during de-pressurisation in different APCS modes

Table 1 Decompression times for simulated depressurisation at different hole diameters (m)

Volume, m^3	Height, km	Decompression time, s					
		0.005 m	0.01 m	0.015 m	0.02 m	0.025 m	Man
	20	–	909.1	404	227.3	145.5	26.83
3	15	–	618.7	275	154.7	98.99	18.26
	10	1506	376.5	167.3	94.12	60.24	11.11
5	20	–	1515	673.4	378.8	242.4	26.83
	15	–	1031	458.3	257.8	165	18.26
	10	–	627.5	278.9	156.9	100.4	11.11
30	20	–	–	–	2273	1455	26.83
	15	–	–	–	1547	989.9	18.26
	10	–	–	1673	941.2	602.4	11.11

real processes. Decompression times are shown in Table 1 and k_{ut} values in Table 2.

2.3 Methodology for assessing human decompression tolerance

To solve the complex task of developing a methodology for assessing human decompression tolerance, two interrelated and interdependent subtasks had to be solved: to substantiate

Table 2 Mass flow rate for simulated depressurisation at different hole diameters (m)

Volume, m^3	Height, km	Mass feed, kg/s				
		0.005 m	0.01 m	0.015 m	0.02 m	0.025 m
3	20	0.002264	0.009051	0.02035	0.03615	0.05641
	15	0.002338	0.009348	0.02102	0.03733	0.05826
	10	0.002449	0.009793	0.02202	0.03911	0.06103
5	20	0.002264	0.009053	0.02036	0.03618	0.05649
	15	0.002338	0.00935	0.02103	0.03736	0.05834
	10	0.002449	0.009795	0.02203	0.03914	0.06111
30	20	0.002264	0.009056	0.02037	0.03622	0.05658
	15	0.002338	0.009353	0.02104	0.0374	0.05844
	10	0.00245	0.009798	0.02204	0.03919	0.06122

exposure tolerance levels and to approximate the dependencies obtained.

When justifying the levels of exposure tolerance medical-biological and physiological-hygienic limitations associated with the use of existing means of pressure parameters control in PC in standard and emergency situations were taken into account. The following adverse factors caused by cabin pressure effects, which depend on flight altitude and APCS operation mode, affect the human body [23, 24]: hypoxic hypoxia (mild, moderate degree), at GC altitudes of 2500–4500 m in normal flight and a pronounced degree PC altitudes up to 12,000 m after depressurisation; hypobaric (moderate to severe) PC altitude from 6000 m in normal flight and severe in PC altitude up to 12,000 m after depressurization; explosive decompression (of moderate and pronounced degree) in case of rapid depressurization in PC from altitude 4500 to 12,000 m; hypothermia (of moderate and pronounced degree) during depressurisation of the PC from − 40 to − 56 °C.

When analysing these factors, three levels of tolerance can be selected that determine the amount of reserve time needed to eliminate the accident: maximum-tolerable, maximum-permissible and permissible levels. These three levels correspond to altitudes of 4.5 km, 6 km and 12 km.

3 Results

The results of calculating the dependence of decompression time on decompression pressure at different leakage ratios are shown in Fig. 2. The dependence of the mass feed on the final cabin pressure is shown in Fig. 3. The results of the simulation of depressurization, presented in Table 1, where approximated by us. The resulting dependence of decompression time on decompression pressure was as follows:

$$\tau_{\text{decom}} = \frac{a}{k_l}, \tag{20}$$

where $a = -0.009 \cdot \ln p_{\text{decom}} + 0.0567$.

We approximated the results of the mass-flow calculations presented in Table 2. The dependence of the final cabin pressure on the mass flow rate at different leakage ratios was as follows:

$$p_{\text{decom}} = a \cdot G_{reg} + b, \tag{21}$$

where $a = 0.1531 \cdot p_{\text{decom}}^2 - 15.2088 \cdot p_{\text{decom}} + 712.6106$, $b = 2.52 \cdot 10^{-11} \cdot p_{\text{decom}}^2 + 7.27 \cdot 10^{-9} \cdot p_{\text{decom}} + 1.49 \cdot 10^{-5}$.

The dependence of the mass flow rate on the final pressure value in the cabin at different leakage rates was as follows:

$$\tau_{\text{decomp}} = a \cdot k_l + b \tag{22}$$

at = 3 m^3: $a = 0.1758 \cdot p_{\text{decom}} + 338.48$, $b = 1.98 \cdot 10^{-8} \cdot p_{\text{decom}} + 2.68 \cdot 10^{-5}$, at $V = 5$ m^3: $a = 0.2931 \cdot p_{\text{decom}} + 564.9815$, $b = 1.98 \cdot 10^{-8} \cdot p_{\text{decom}} + 1.49 \cdot 10^{-5}$, at $V = 30$ m^3: $a = 1, 767 \cdot p_{\text{decom}} + 3395, 422$, $b = 1.64 \cdot 10^{-10} \cdot p_{\text{decom}}^2 - 3.97 \cdot 10^{-8} \cdot p_{\text{decom}} + 3.83 \cdot 10^{-6}$.

4 Discussion and conclusions

The study of the problem of safety during AC depressurisation has been conducted in an interconnected manner, both from the physiological and technical points of view, which made it possible to investigate different modes of APCS operation. The process of air outflow from the aircraft AC during depressurisation was investigated from the standpoint of the theory of thermodynamics of a variable mass body under increasing external backpressure, i.e. in conditions of emergency descent to a safe altitude. The results made it possible to quantitatively estimate the degree of safety and identify the possibility of ensuring safety during the descent of aircraft from different altitudes. An essential result of the work is the development and justification of a comprehensive

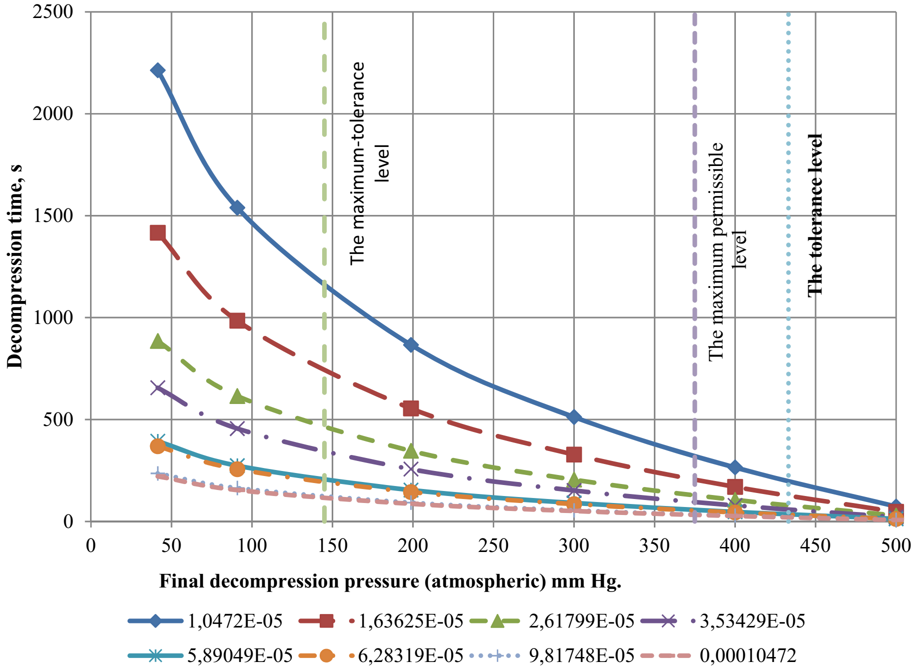


Fig. 2 Decompression time at different leakage rates

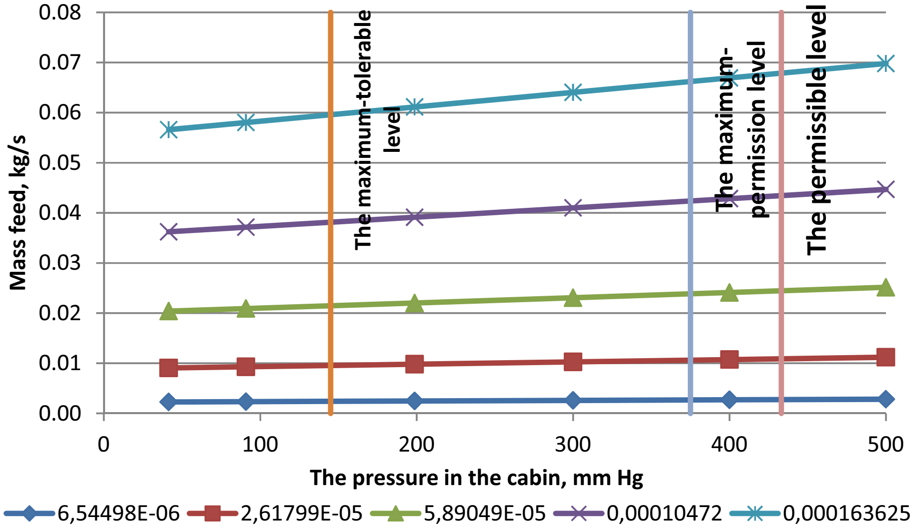


Fig. 3 Dependence of mass flow rate on pressure in the cabin at different leakage coefficients at a volume of 3 m^3

simulation model of gas dynamic processes during decompression of sectioned ACs, which can be used as a universal mathematical tool in solving a wide range of practical problems associated with breach of air tightness, regulation of air parameters, supercharging and ventilation.The versatility of the developed mathematical model also allows to use it for solving a wide variety of problems arising in designing complex systems of aircraft equipment supercharging and ventilation, communicating gas tanks in the presence of gas inflow and/or outflow, conditioning and ventilation systems of industrial facilities, underwater ships, underground structures, shelters, etc.

The resulting model allows, at the design stage, to make a rational choice of pressurised and gas dynamic PC parameters, as well as flight-operating characteristics of the aircraft taking into account possible cabin decompression in flight or, on the contrary, at given parameters and flight data to assess the degree of danger in case of depressurization and to provide a set of safety measures in advance, as follows: select rational proportions of volume of PC of the designed aircraft; determine the magnitude of pressure differences arising from decompression between communicating compartments, and hence the loads acting on structural elements for strength calculations; determine design measures to prevent the occurrence of dangerous pressure drops in the communicating compartments; determine necessary speed of aircraft descent to a safe altitude in case of PC decompression from the pilot's physiological safety; select cruising altitude for the aircraft taking into account possible cockpit decompression and permissible rate of descent to a safe altitude; quantify the effect of increasing the duration of acceptable time of occupant's stay in PC in the process of decompression at a given rate of emergency descent; evaluate the effectiveness of oxygen and breathing apparatus and APCS depending on the depressurisation altitude and the permissible emergency descent rate to a safe altitude.

Author contributions All authors were involved in the conception and design of the study. Preparation of the material was done by AR, IM and AM. The first draft of the manuscript was written by TM and MD, and all authors commented on previous versions of the manuscript. All authors read and approved the final version of the manuscript.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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