Design concept of onboard air purification system for commercial aircraft

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Abstract. The purpose of the article is to discuss methods of air disinfection in passenger aircraft cabins during flight. In the course of the study, a comparative analysis of modern methods of cleaning and disinfecting air in closed rooms was carried out. The efficiency, mass characteristics and energy consumption of UV sources are compared. The use of photocatalytic filters based on the phenomenon of oxidation of organic substances under the influence of sunlight in the presence of a catalyst is proposed. As a result, the authors compare the efficiency of disinfection and energy consumption when using various methods of air purification. In addition, the authors draw conclusions about the prospects of the proposed method of air disinfection using photocatalytic filters in relation to the cabins of passenger aircrafts. The schemes of rational placement of UV sources are proposed, which allow obtaining the maximum efficiency of air disinfection.

1. Introduction

From the epidemiological point of view, the cabin of a passenger plane is perhaps the most favorable place for the spread of infectious diseases as the transmission of infections is almost inevitable during a long flight in a closed space of the cabin.

The standard ventilation system of airplane cabins draws in outside air and takes air out of the compressor. The mixing of these two streams gives air that is acceptable to humans in terms of pressure and oxygen saturation. It also provides the recirculation and mechanical filtration of air.

However, mechanical fine filtration is not able to purify the air from viruses. In order to combat the spread of infectious diseases on board of an aircraft, it is required to introduce disinfecting elements into the air filtration system.

2. Materials and methods

The most common methods widely used in medical practice include filtration, ultraviolet irradiation, disinfection with aerosols of chemical disinfectants and ozonation [1].

Air filtration used in aviation air conditioning systems (ACS) effectively removes dust particles from the air and the use of fine filters and HEPA filters can trap even some relatively large microorganisms. High Efficient Particle Arrestance or highly efficient particle retention are the filters the action of which is based on the deposition of the smallest particles of contamination on chaotically located fibers due to the forces of intermolecular interaction. Such filters are much more effective for retaining fine particles than filters operating like sieves.
However, as it is mentioned above, a mechanical filter of any fine purification is not able to stop the spread of viruses due to their extremely small size (up to 0.02 microns). In addition, microorganisms are not destroyed in the filters. In the case of the slightest malfunction of the filter, quite viable bacteria and viruses will enter the recirculation system. Thus, we can conclude that mechanical filtration is necessary but insufficient in air purification systems.

Ozonation of air is an effective method of disinfection. However, it requires proper ventilation of the room or maintenance of the period of decomposition of ozone to oxygen (at least several hours). For obvious reasons, this method is not suitable for onboard ACSs.

It is possible to consider the use of ozone-rich air taken from behind the board for disinfection.

Air disinfection using chemical aerosols can be a fairly effective method. However, chemicals that are dangerous for bacteria and viruses, as a rule, are dangerous for humans. That is why it necessitates proper ventilation of the premises and compliance with additional safety measures when working with toxic substances. In addition, during the use of this method of air disinfection, in order to create aerosols it will be necessary to keep chemicals on board, which will increase the weight of the aircraft.

According to the above mentioned, we can conclude that the described disinfection method is not applicable for on-board air conditioning systems.

The method of air disinfection using ultraviolet rays is perhaps the most common today.

Ultraviolet radiation has a less wavelength (100 ... 400 nm), frequency and energy are higher than that of the visible spectrum. The UV range is divided into the ranges UV-A (wavelength 315 - 400 nm), UV-B (280 - 315 nm) and UV-C (100 - 280 nm).

In nature, UV-B and UV-C radiations do not reach the surface of the Earth, since they are trapped by the ozone layer of the atmosphere. Accordingly, terrestrial microorganisms can not be adapted to such an impact and, for the most part, do not have mechanisms of protection against it.

Hard ultraviolet light (UV-B and UV-C ranges) irreversibly damages the structure of DNA or RNA of microorganisms. Since it is DNA (or, in the case of viruses, RNA) that is responsible for the multiplication of cells, their damage leads to the death of microorganisms.

It is necessary to note that the absorption spectra of different DNA and RNA do not coincide, as a result of which the dependence of the bactericidal and virucidal efficiency of UV radiation on the wavelength has a form close to the normal distribution (Figure 1) [11].

As it can be seen in the graph the maximum bactericidal and virucidal efficiency of radiation is presented by UV-C range with a maximum of nearly 265 nm.

Mercury and amalgam UV lamps have a radiation wavelength of 254 nm [3], which is close to the peak of the curve. However, as it is mentioned above, not all microorganisms have absorption lines coinciding with a given wavelength.

Xenon lamps with a wide range of radiation “cover” the entire bactericidal range, but because of this, they are energy-ineffective and have an extremely low efficiency rate [4].

In addition, the continuous range of xenon lamps (from 190 to 400 nm [5]) in its short-wavelength part is ionizing and leads to the formation of ozone from oxygen in the air. Ozone, as it is already mentioned, is toxic to humans.

It is necessary to note that killing some microorganisms, UV emitters thereby create a breeding ground for the reproduction of others: strains that are more resistant to ultraviolet light can parasitize on their remains. Thus, the use of ultraviolet emitters potentially creates the conditions for the development of a strain of pathogenic microorganisms that are completely resistant to ultraviolet light. Such situation is highly undesirable.

It also necessary to take into account that ultraviolet radiation, especially short-wavelength, is dangerous for humans, as a result it is necessary to install ultraviolet lamps in closed boxes and follow increased labor safety requirements when repairing and replacing them.

In this regard, it can be concluded that the use of on-board ultraviolet air disinfectants is generally possible, but it creates a number of rather serious difficulties.
Figure 1. Dependence of the bactericidal and virucidal efficiency of ultraviolet radiation $S$ on the wavelength $\lambda$.

3. Results and Discussion

A promising method of air disinfection is the use of photocatalytic filters, which are based on the phenomenon of oxidation of organic substances under the influence of sunlight in the presence of a catalyst. On board the aircraft, solar radiation can be replaced with lamps of the appropriate spectrum.

Photocatalysis is the phenomenon of excitation of chemical reactions under the action of light in the presence of certain substances (photocatalysts), which, as a result of absorption of light quanta by them, are capable to cause chemical transformations of the participants in reactions, entering into intermediate chemical interactions with the latter and regenerating their chemical composition after each cycle of such interactions [6].

The most famous and widespread photocatalyst is titanium dioxide $\text{TiO}_2$, a solid substance that can decompose low molecular weight organic (viruses, bacteria, fungal and mold spores) and inorganic (formaldehyde, carbon monoxide) air pollutants to simple oxides [7] in the presence of sunlight.

Titanium dioxide is a semiconductor, that is, the electrons inside it are bound (located in the valence band) and must cross the forbidden band in order to enter the conduction band. The band gap is about 3 eV (the values may differ for different modifications).

In order to overcome the band gap, an electron must absorb a quantum of light with a wavelength of no more than 390 nm, which corresponds to UV-A radiation range. As a result of the transition of an electron to the conduction band, a hole remains in the valence band - a quasiparticle with a positive charge, numerically equal to the electron charge:

$$TiO_2 + h\nu \rightarrow h^+ + e^-.$$ 

Holes and electrons are free charge carriers. Reaching the surface of the crystal, they start a cascade of reactions with oxygen and water vapor in the air:

$$e^- + O_2 \rightarrow O_2^-;$$  
$$O_2^- + e^- \rightarrow O_2^{2-} \rightarrow O^- + O^-;$$  
$$O_2^{2-} + 2H^+ \rightarrow H_2O_2;$$  
$$H_2O_2 + e^- \rightarrow OH^+ + OH^-;$$  
$$O^- + e^- \rightarrow O^{2-};$$
The resulting ions $O^-$ and $OH^+$, which have the highest chemical activity, decompose organic compounds to simple oxides:

$$OH^+ + \text{organic compound} \rightarrow H_2O + CO_2;$$

$$O^- + \text{organic compound} \rightarrow H_2O + CO_2. \quad [8]$$

In photocatalytic filters, where it is impossible to provide constant access to direct sunlight, low-frequency ultraviolet emitters with a wavelength of 320-400 nm are used. Ozone is not formed when oxygen in the air is irradiated with light of this range.

The advantages of this method include the fact that photocatalytic filtration completely destroys any organic matter suspended in the air, including low molecular weight organic compounds that create unpleasant odors in the aircraft cabin.

In addition, the power consumption of photocatalytic filters is much lower than that of traditional UV emitters, which is important in the design of onboard systems.

The disadvantages of this method include the toxicity of titanium dioxide when nanoparticles are inhaled. To prevent this, titanium dioxide is bound using various physicochemical methods and, as a rule, it is placed on some kind of fibrous substrate [16].

It is known that the maximum efficiency of photocatalysis is achieved at a specific power of ultraviolet radiation from 2 to 10 $\mu$W per square centimeter of the geometric surface of the photocatalyst [11]. Since it is the radiation power that is the limiting factor of photocatalysis, we will calculate it from the condition of its provision.

For convenience of calculations, we will express the area in mm$^2$, and the power-in $\mu$W. Then it turns out that it is necessary to provide a specific power in the range of 20...100 $\mu$W/cm$^2$.

One CUN6HF4A lamp with a wavelength of 365 nm produced by Seoul Viosis (today's leading manufacturers of UV LEDs) has a power of $P_0 = 4.3$ W = 4300000 $\mu$W [20].

During bench tests, it was found that one lamp with a power of $P'_0$ of 8.8 W in the ultraviolet range [21] is sufficient for continuous air purification at a volume flow rate of $Q_0 = 30$ m$^3$/h [11].

The mass flow rate of air $Q_M$ through each of the recirculation fans is 1600 kg/h at a temperature of 25°C and pressure as at an altitude of 1800 m. The air density $\rho$ with such characteristics of the medium is 1.02694 kg/m$^3$. Accordingly, the volume flow of air through the fan:

$$Q = \frac{Q_M}{\rho} = \frac{1600}{1.02694} \approx 1558 \text{ m}^3/\text{h}.$$

Thus, the equivalent number of lamps with a power of 8.8 W in one photocatalytic filter on board the aircraft is:

$$n = \frac{Q}{Q_0} = \frac{1558}{30} = 51.9.$$

Then the number of LEDs:

$$N = n \frac{P'_0}{P_0} = \frac{51.9 \cdot 8.8}{4.3} = 106.3.$$

Rounding to integers, we get:

$$N = 107 \text{ pcs}.$$

At the same time, the minimum irradiated area will be (at the rate of 100 $\mu$W/cm$^2$):
It is necessary to provide a rational way of placing LEDs (LED strips) in such a way that the filter has a sufficient area of the irradiated surface.

It seems rational to arrange the LEDs in a row on one of the sides, and cover the inner surface of the cylinder with a material coated with titanium dioxide nanoparticles (Figure 2). The introduction of additional surfaces significantly increases the irradiated area.

![Figure 2](image)

**Figure 2.** The proposed design of the photocatalytic filter: 1 - LED; 2 - housing; 3 - photoactive material; 4 - additional surfaces.

It should be noted that the lighting angle of the LEDs is 115°. It will be necessary to provide reflectors for the effective operation of LEDs during the technical design (Figure 3).

The most rational one is the placement of disinfecting elements (FP1, FP2) on the suction line after the mechanical filter (F1, F2) (Figure 4). The electric fan (EF1, EF2) of the suction line will provide the necessary air draft, and a mechanical filter of a high degree of purification will increase the resource of the disinfecting element.

The increase in the take-off weight of the aircraft will be minimal.

It should also be noted that the introduction of such a method of air purification will require minimal design changes and can, if necessary, be carried out on already operated aircraft.
Figure 3. Operation of reflectors (the dashed lines show the course of the light rays)

Figure 4. Layout of photocatalytic filters in the air conditioning system of a twin-engine aircraft

4. Conclusion
Based on the above aspects, it can be concluded that the most rational methods of air disinfection are its ultraviolet irradiation and photocatalysis of suspended organic substances. Both of these methods do not imply significant changes in the composition of the air conditioning system. Moreover, they do not require additional consumables on board and have a reliable justification for their own effectiveness. In addition, they are very similar to each other in many ways.

At the same time, photocatalytic air disinfection has a number of advantages. The main ones are low energy consumption, high bactericidal and viricidal efficiency and a small mass of active elements. The proposed schemes of placement of ultraviolet emitters and design solutions of additional filters will minimally affect the weight of the onboard system and ensure high efficiency of air disinfection.
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