МАШИНОСТРОЕНИЕ
2.5.12 – Аэродинамика и процессы теплообмена летательных аппаратов;
2.5.13 – Проектирование конструкция и производство летательных аппаратов;
2.5.14 – Прочность и тепловые режимы летательных аппаратов;
2.5.15 – Тепловые электроракетные двигатели и энергоустановки летательных аппаратов;
2.5.16 – Динамика, баллистика, управление движением летательных аппаратов

УДК 629.7.016:533.68
DOI: 10.26467/2079-0619-2022-25-2-70-80

Impact of the atmosphere state on interaction of aircraft vortex and condensation trails

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Abstract: Currently, much emphasis is given to the environmental problems. This article is not an exception. It is devoted to the issue of propagation and interaction of vortex and condensation trails that form behind aircraft when flying in the atmosphere, depending on its state. A vortex trail is an area of disturbed air flow behind an aircraft formed as a result of its motion. A condensation trail is a product of the aviation fuel combustion in the engine and represents condensed moisture in the form of ice crystals, which is generated under certain ambient conditions. As the numerous studies and observations have shown, condensation trails can affect the heat exchange processes in the atmosphere, contributing to the greenhouse effect, deteriorate the environment. It is especially relevant for the area where numerous transitional airways pass. Therefore, it is essential to understand behind what aircraft type the condensation trail, interacting with the vortex one, dissipates in the atmosphere, and the substances composing the condensation trail lose their concentration. And on the contrary, behind what aircraft type the condensation trail does not dissipate for a long term, and the substances, composing the contrail, retain concentration for a long time. It should also be noted that the contrail, while interacting with the vortex wake, can reveal its structure and visualize the processes of propagation and attenuation of the vortex wake. This paper uses a special computational software application, based on the discrete vortex method, to study the interaction of condensation and vortex trails. It considers the flight weight, aircraft speed and altitude, its in-flight configuration, atmospheric conditions, axial velocity in the vortex core and some other factors, when calculating the vortex wake performance. This complex passed the required testing and state registration. Several procedures were executed to validate and verify the developed complex, confirming its program efficiency and the reliability of the results obtained. The Airbus A320 and A380 were selected as the research object of this article. The flight mode and atmospheric conditions are similar for all aircraft. The results obtained allow us to understand how atmospheric conditions affect the propagation of contrails behind aircraft of different classes, provided their interaction with vortex trails.

Key words: ecology, condensation trail, vortex wake, aircraft, interaction of trails, concentration.

For citation: Zhelannikov, A.I., Zamyatin, A.N. & Chinyuchin, Yu.M. (2022). Impact of the atmosphere state on interaction of aircraft vortex and condensation trails. Civil Aviation High Technologies, vol. 25, no. 2, pp. 70–80. DOI: 10.26467/2079-0619-2022-25-2-70-80

Влияние состояния атмосферы на взаимодействие вихревых и конденсационных следов воздушных судов

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Аннотация: В настоящее время много внимания уделяется экологическим проблемам. Данная работа не исключение. Она посвящена проблеме распространения и взаимодействия вихревых и конденсационных следов, образующихся за воздушными судами при полете в атмосфере в зависимости от ее состояния. Вихревой след – это область возмущенного воздушного потока за самолетом, образующаяся в результате его движения. Конденсационный след является продуктом сгорания авиационного топлива в двигателе и представляет собой сконденсированную влагу в виде ледяных кристаллов, которая образуется при определенных состояниях атмосферы. Как показали многочисленные исследования и наблюдения, конденсационные следы могут влиять на теплообменные процессы в атмосфере и, способствуя парниковому эффекту, ухудшать экологию. Особенно это актуально для местности, где проходят многочисленные воздушные транзитные трассы воздушных судов. Поэтому важно понимать, за какими воздушными судами конденсационный след, взаимодействуя с вихревым, рассеивается в атмосфере, а вещества, входящие в состав конденсационного следа, теряют свою концентрацию. И, наоборот, за какими воздушными судами конденсационный след долго не рассеивается, а вещества, входящие в состав конденсационного следа, длительное время сохраняют концентрацию. Отметим также, что конденсационный след, взаимодействуя с вихревым следом, может выявлять его структуру, а также визуализировать процессы распространения и затухания вихревого следа. В данной статье для исследования взаимодействия конденсационных и вихревых следов был использован специальный расчетно-программный комплекс, базирующийся на методе дискретных вихрей. В нем при расчете характеристик вихревого следа учитываются полетный вес, скорость и высота полета самолета, его полетная конфигурация, атмосферные условия, осевая скорость в ядре вихря и некоторые другие факторы. Этот комплекс прошел необходимую апробацию и государственную регистрацию. Был выполнен ряд мероприятий по валидации и верификации разработанного комплекса, подтверждающих работоспособность программ, входящих в него, и достоверность получаемых результатов. В данной статье в качестве объектов исследования были выбраны воздушные суда А-320 и А-380. Режим полета и атмосферные условия для всех самолетов выбраны одни и те же. Получены результаты, которые позволяют понять, как влияют атмосферные условия на распространение конденсационных следов за воздушными судами разного класса при условии их взаимодействия с вихревыми следами.

Ключевые слова: экология, конденсационный след, вихревой след, воздушное судно, взаимодействие следов, концентрация.

Для цитирования: Желанников А.И., Замятин А.Н., Чинючин Ю.М. Влияние состояния атмосферы на взаимодействие вихревых и конденсационных следов воздушных судов // Научный Вестник МГТУ ГА. 2022. Т. 25, № 2. С. 70-80. DOI: 10.26467/2079-0619-2022-25-2-70-80

Introduction

It is known that under certain flight conditions, a contrail is formed behind flying aircraft (fig. 1). When aviation fuel combusts in the engine at the outlet of the nozzle, there is water vapor among other combustion products. Under certain atmospheric conditions, this water vapor together with atmospheric moisture condense in the form of drops and ice crystals and become visible [1–4]. As the numerous studies and observations have shown, contrails degenerate into thin cirri high-altitude clouds as time progresses and can affect the Earth's climate, as well as the heat exchange processes in the atmosphere, contributing to the greenhouse effect and deteriorating ecology. This is especially relevant for the areas with intensive air traffic, where numerous airways pass. At present, various methods to reduce or even eliminate the contrail are being developed. For example, if ultra-low sulfur fuel is used, it is claimed by the authors that the contrail can be almost fully eliminated (US Applica-

Fig. 1. Example of a condensation trail behind an airplane

tion No. 12/614,640 dated November 9, 2009). The options for changing the altitude and flight route are also considered, but these alternatives can lead to an increase in flight time, which means additional carbon dioxide emission [2, 3]. A local increase in carbon dioxide can result in acid rain [1–4]. Several works [5–7] study aircraft vortex and contrails. This research has shown that contrails behind aircraft of modern aerodynamic configuration of the Airbus A320 and A380 types are drawn into wake vortices and their further propagation in the atmosphere depends on a variety of factors. Among these factors we can mention the flight speed and altitude, aerodynamic configuration of the aircraft, its flight configuration, as well as the atmospheric conditions in which a flight operates [8–14]. The paper [1] shows that some aircraft aerodynamic configuration can have a favorable effect on contrail propagation, in terms of its dispersion in the atmosphere. The engines of these aircraft are located short of the wingtip, which means that tip vortices releasing the wing, capture the contrail and disperse it partially or completely, thus reducing the negative impact of the contrail on the environment.

On the other hand, if the contrail is not drawn into the wake vortex, and there are such aircraft aerodynamic configurations, its propagation in the atmosphere will occur according to the physical principles. In the non-turbulent atmosphere, the contrail can remain long, but in the turbulent atmosphere it can do considerably shorter [1].

This article explores the process of contrail propagation under the conditions of its interaction with wake vortex. The wake vortex effect on the contrail is prioritized but not atmospheric turbulence. It is common knowledge that [12–18], the atmospheric turbulence effect is by an order of magnitude weaker than wake vortex. Wake vortex propagation, in its turn, depends significantly on the ambient conditions [5].

It is known [2, 3, 5] that the ambient conditions can vary from highly stable to highly unstable, depending on the turbulent processes occurring in the meteorological atmosphere. This article carries out the study of the various atmospheric conditions effect on contrail propagation in the conditions of its interaction with wake vortex.

Methodology of the research

The studies on the interaction and propagation of vortex and condensation trails were carried out using the computational software application [15] which basics and ideas are described in the monographs [5–18] and articles [19–23].

The foundation of the computational software application is a mathematical model of the long-range wake vortex [5], in which speeds disturbed by aircraft are obtained, based on an accurate solution of the Helmholtz equation [17]. This allowed us to consider the dissipation and diffusion of vortices, modeling wake vortex. These phenomena are associated with the natural process of vortices attenuation in the meteorological atmosphere. The contrail was modeled in the following way: eight markers, which simulated the contrail boundary, were located around the nozzle contour of each engine. Another marker was placed in the center of the nozzle.

Таблица 1
Table 1

Assessment of ambient conditions

Richardson number Ri	Ambient condition (AC)	Estimates
$Ri < -1.0$	Highly unstable	5
$-0.01 > Ri \geq -1.0$	Unstable	4
$0.01 \geq Ri \geq -0.01$	Neutral	3
$2.5 \geq Ri > 0.01$	Steady	2
$Ri > 0.25$	Highly stable	1

The markers were considered weightless. The problem was solved in a nonlinear non-stationary setting by the method of discrete vortices. The markers moved in space within the time frame, considering the effect of aircraft wake vortex. The problem was solved in the dimensional format; therefore, the graphs below show calculation data for the specific aircraft flight conditions. In order to simplify understanding of the process of vortex and contrails interaction, the graphs below only monitor the marker movement, which was placed in the center of the nozzle. The paper [1] shows the movement of other markers, which simulate the engine contour.

To assess the ambient condition in the mathematical model of the long-distance wake vortex of the computational software application, the Richardson number was used.

$$Ri = \frac{g}{\overline{T}} \frac{\Delta\overline{T} / \Delta z}{(\Delta N / \Delta z)^2}.$$

Here g is acceleration of free fall, T is the average temperature of the layer Δz thick. $\Delta\overline{T} / \Delta z$ and $\Delta\overline{N} / \Delta z$ are respectively the average horizontal wind velocity temperature gradients in the layer Δz thick.

The Richardson number characterizes the ratio of buoyancy forces (numerator) and dynamic factor (denominator), id est, the ratio of the contributions of free and forced convection in the formation of atmospheric turbulence. Thus, the increase in the temperature gradient modulus corresponds to the state in which buoyancy forces dominate. The increase in the velocity gradient corresponds to the increase in the dynamic factor and characterizes the atmosphere as unstable. The ambient condition is considered neutral if $-0.01 \leq Ri \geq 0.01$, in this case, the thermal influence is minimal so only forced convection can exist. When the $Ri < -0.01$ number decreases, buoyancy forces become more apparent, mixed convection arises, and at $Ri < -1.0$, a free convection mode is established. On the contrary, with an increase in $Ri > 0.01$ buoyancy forces begin to impede the turbulence development. At $Ri > 0.25$ the current becomes almost laminar, turbulent mixing is virtually absent.

So, at $Ri < -1.0$ the ambient condition is considered highly unstable (AC = 5), at $-0.01 > Ri \geq -1.0$ unstable (AC = 4), at $0.01 \geq Ri \geq -0.01$ neutral (AC = 3), at $2.5 \geq Ri > 0.01$ steady (AC = 2) and at $Ri > 0.25$ highly stable (AC = 1). All the above argumentations can be narrowed down to Table 1.

To make the application of this table and the introduction of initial data into the mathematical model of long-distance wake vortex convenient, the ambient condition estimates are given. A highly unstable atmosphere is rated at 5 points, and strongly stable at 1 point. From Table 1, we can see the estimates of other ambient conditions. The flight experiments as well as the observations of real aircraft flights showed that the position and propagation of vortex as well as aircraft contrails significantly depend on the ambient condition. In a non-turbulent atmosphere, vortex trails exist for prolonged time, while in the unstable atmosphere they quickly disappear due to dissipation and diffusion. It means, contrails, when interacting with vortex ones, will behave differently. The rapid destruction of the wake vortex in a highly unstable atmosphere leads to the cessation of its effect on the contrail, which can exist for more extended time. Vice versa, the long-term existence of wake vortex in a highly stable atmosphere leads to the rapid destruction of the contrail and its dispersion in the atmosphere. Turbulence of the atmosphere itself also affects the contrail dispersion. This mathematical model also takes into consideration this fact.

Results of the research

Twin-engine Airbus A320 and four-engine A380 were chosen as the objects of this investigation. The similar flight mode and atmospheric conditions were chosen for both aircraft. The altitude was H = 10,000 m, air speed V = 850 km/h, the distance behind the aircraft, to which vortex and contrails were calculated, was equal to 25 km. The Airbus A320 and A380 weight came to 77 tons and 560 tons respectively. Furthermore, the ambient condition, in the calculations, was introduced as highly stable (AC = 1), neutral (AC = 3) and highly unstable (AC = 5) in accordance with Table 1. In the graphs below, all linear dimensions are made on a scale for the convenient perception.

Figure 2 represents the calculation results for position of the Airbus A320 contrails in a highly stable atmosphere (AC = 1). Herewith, the movement of the marker in the oval form, originally located in the center of the nozzle, is shown. The time of wake vortex impact on the contrails will be assessed by the length of its trajectory. The longer the trajectory is, the longer the interaction time of these trails. The vertical axis of the charts shows the aircraft altitude H (m), so does the horizontal axis – the distance (offset) to the right from the aircraft Z (m). The presented trajectories of the marker are obtained by taking into consideration the Airbus A320 wake vortex effect. The vortex trail exists in the non-turbulent atmosphere for a long space of time.

We can see that the vortex trail, having captured the condensation one, commences long interaction with it, thereby, more diffuses it in the atmosphere.

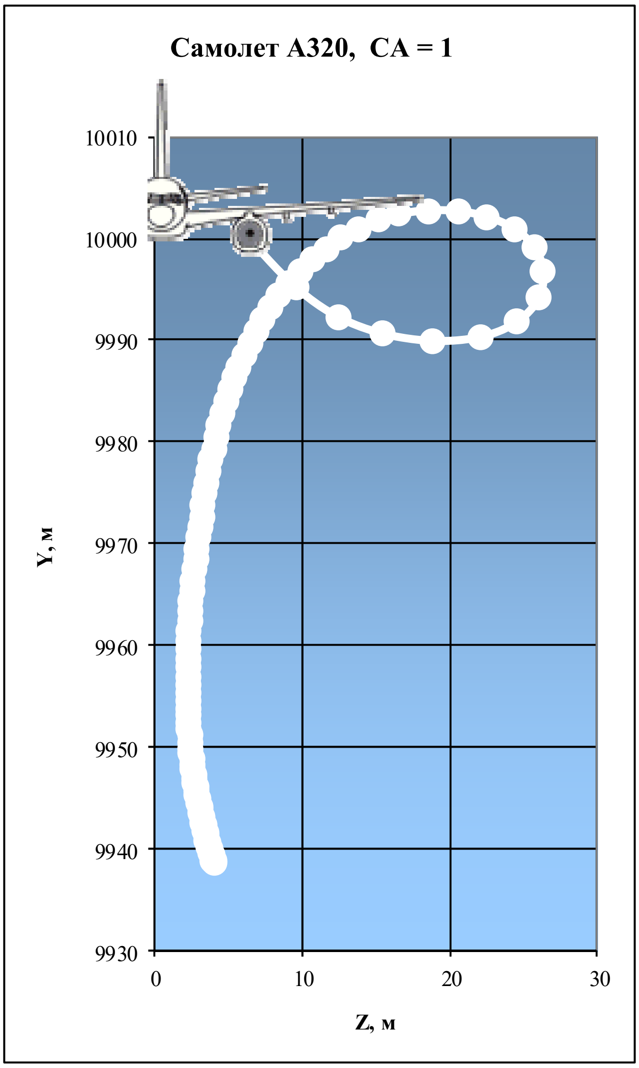

Fig. 2. Propagation of a condensation trail in a highly stable atmosphere

Figure 3 shows the calculation results of position of the Airbus A320 contrails in a neutral atmosphere (AC = 3).

In this case, due to atmospheric turbulence, the vortex trail fades faster. As in a highly stable atmosphere, after capturing the contrail, it disperses. But here the time for dispersing the trail is significantly shorter. In gusty air (AC = 5), the vortex trail fades more quickly and its interaction with the contrail, weakens more greatly (fig. 4).

The contrail retains its structure and concentration of inclusive substances for a long time. The contrail “hangs” at one height. In this case,

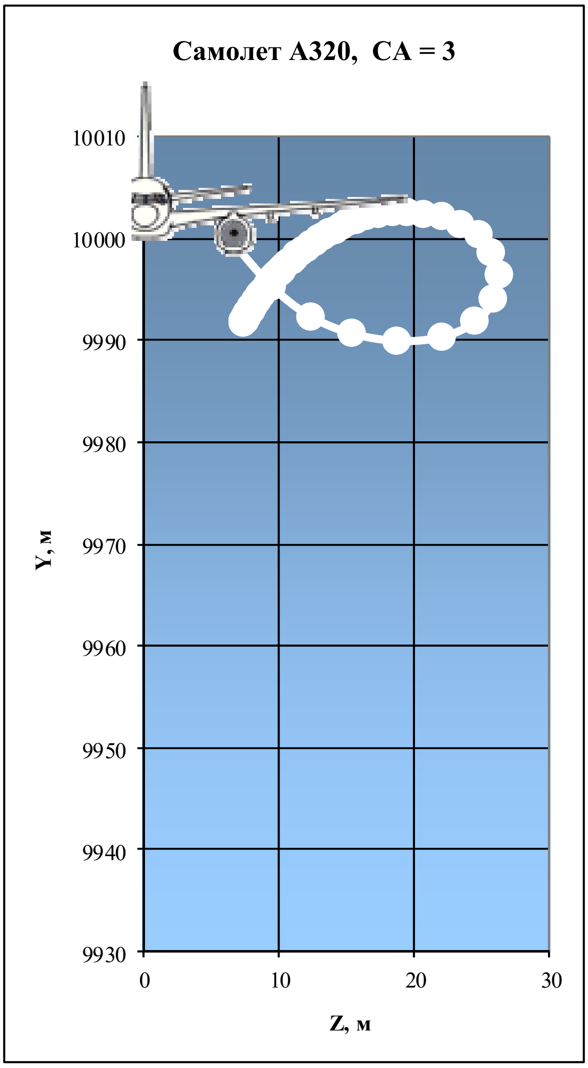

Fig. 3. Propagation of a contrail in a neutral atmosphere

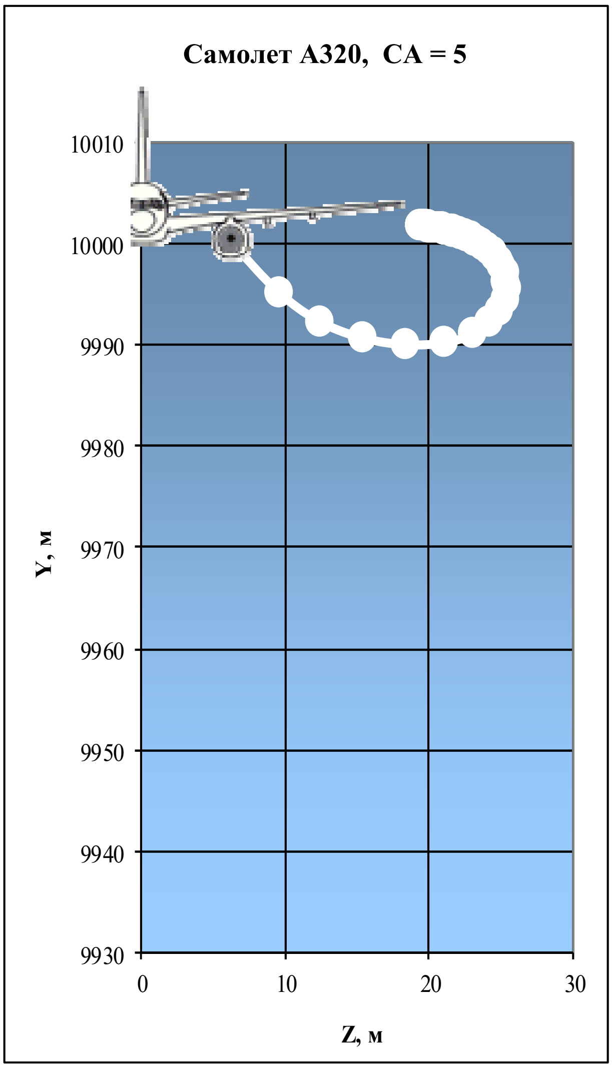

Fig. 4. Propagation of a contrail in a highly unstable atmosphere

only processes, taking place in a turbulent atmosphere, have an impact on it. Let us take notice that these processes in their effect are by an order of magnitude weaker than the vortex trail effect [12, 15].

The similar results are obtained for the Airbus A380. Figure 5 shows the calculation results of the contrail position in a highly stable atmosphere. The movement of two markers, originally located in the center of each engine nozzle, is also shown. The presented trajectories of markers are obtained by means taking into consideration the Airbus A380 vortex trail effect. The argumentation for the Airbus A320 is also reasonable. In the non-turbulent air (AC = 1), the vortex trail, having captured the contrail and interacting with it, disperses quickly it in the atmosphere. In a neutral atmosphere (AC = 3), the vortex trail fades faster than in a highly stable atmosphere. Therefore, the contrail dispersion time is substantially shorter (fig. 6). In a turbulent atmosphere (AC = 5), the vortex trail fades more quickly and its interaction with the contrail weakens more greatly (fig. 7).

The contrail retains its structure and, therefore, the concentration of inclusive substances. In this case, only processes, taking place in a turbulent atmosphere, affect it. But these processes in their effect, as it has been noted above, are by an order of magnitude weaker than the vortex trail effect [12, 15].

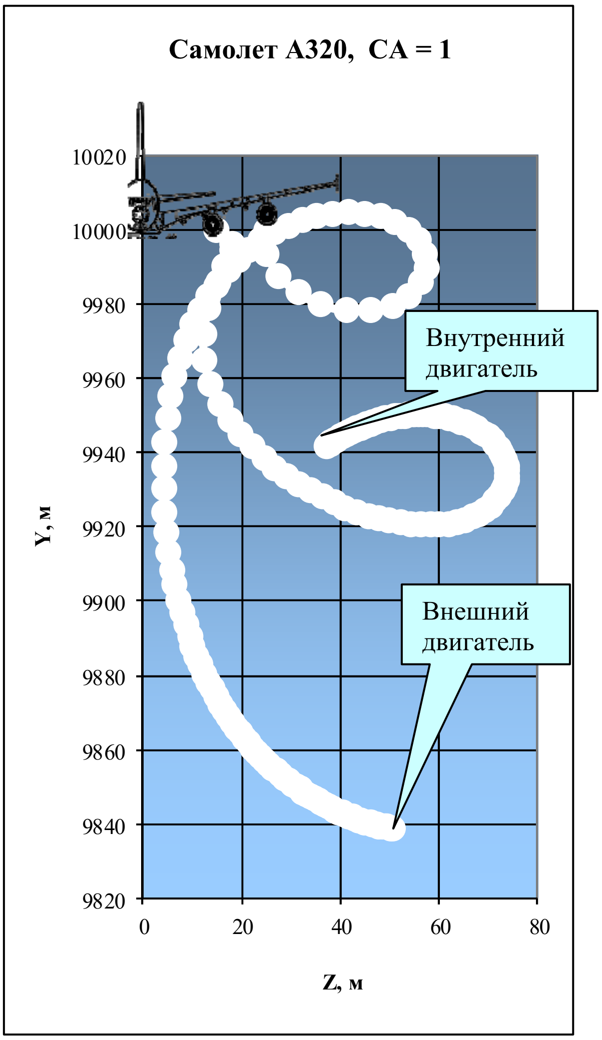

Fig. 5. Propagation of a condensation trail in a highly stable atmosphere

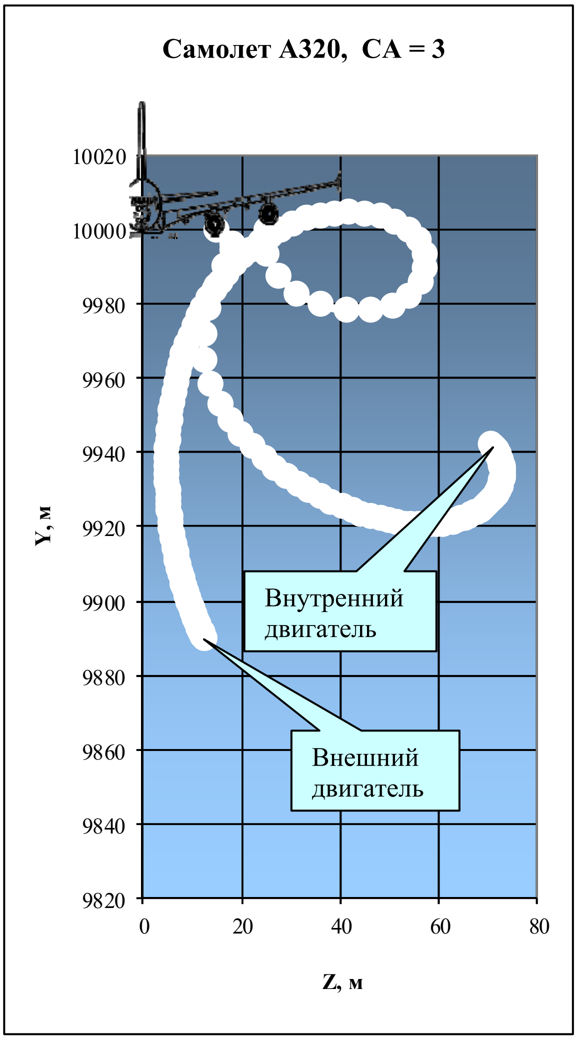

Fig. 6. Propagation of a condensation trail in a neutral atmosphere

Conclusion

Thus, the calculations showed that in case of the vortex and contrails interaction, the diffusion of the contrail behind aircraft substantially depends on the ambient condition. In a highly stable atmosphere contrail dissipates fastest of all. Here, the vortex trail remains long and affects the contrail continuously. Subsequently, the concentration of inclusive substances decreases due to the longer time of interaction. Conversely, in a highly unstable atmosphere, the vortex trail fades rapidly and its effect on the contrail weakens, afterwards it disappears entirely. The contrail "hangs" at the same height. In this case, only processes that happen in a turbulent atmosphere, which, as it has been noted above, in terms of their effect on the contrail, are by an order of magnitude weaker than the vortex trail impact. The contrail retains its structure and concentration of inclusive substances for a longer stretch of time.

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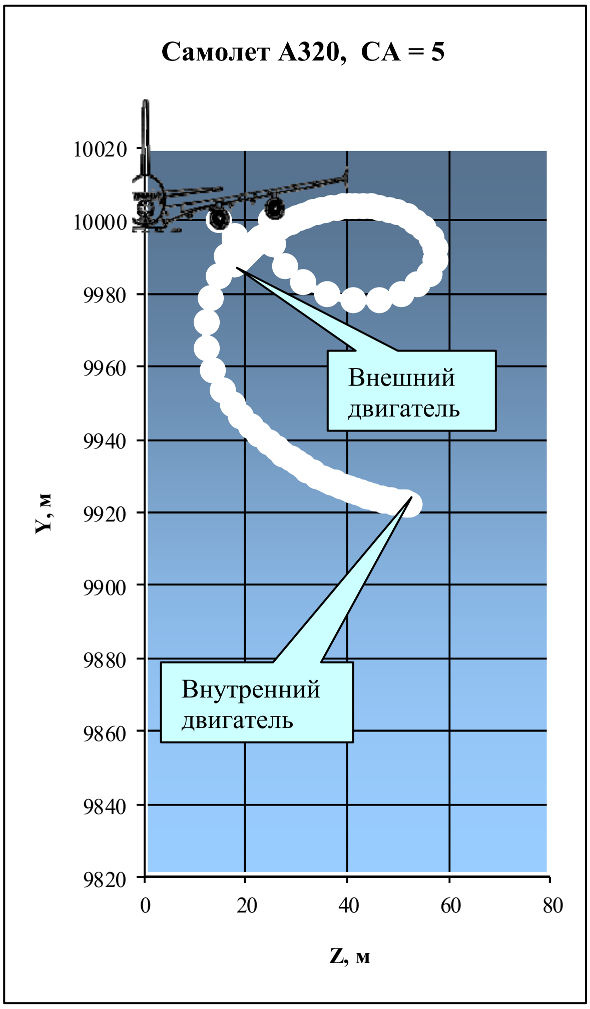

Fig. 7. Propagation of a condensation trail in a highly unstable atmosphere

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Поступила в редакцию	13.01.2022	Received	13.01.2022
Принята в печать	24.03.2022	Accepted for publication	24.03.2022

ББК 05
Н 34
Св. план 2022

Научный Вестник МГТУ ГА
Том 25, № 02, 2022
Civil Aviation High TECHNOLOGIES
Vol. 25, No. 02, 2022

Свидетельство о регистрации в Федеральной службе по надзору в сфере связи,
информационных технологий и массовых коммуникаций (Роскомнадзор) ПИ № ФС77-47989
от 27 декабря 2011 г.

Оформить подписку на печатную версию журнала можно на сайте Объединенного каталога «Пресса России» www.pressa-rf.ru. Подписной индекс 84254.

Подписано в печать 25.03.2022.

Печать цифровая Формат 60×90/8 10,0 усл. печ. л.

Заказ № 915/39 Тираж 50 экз.

Московский государственный технический университет ГА
125993, Москва, Кронштадтский бульвар, д. 20
Изготовлено в ИД Академии имени Н. Е. Жуковского
125167, Москва, 8-го Марта 4-я ул., дом 6А
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