COMPARATIVE ANALYSIS OF CONDITIONS FOR DEVELOPMENT OF ANTHROPOGENIC AND ARTIFICIAL CLOUDS AND FOGS ABOVE SEA

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The results of numerical, laboratory, and field experiments on creation and development of artificial cloudy formations downstream of sea ships are presented. The development conditions are shown to be identical to those of cloudy formations of the anthropogenic origin. These conditions can be changed thus enabling to lower, to a certain extent, the probability of formation of anthropogenic clouds or to stimulate creation of artificial clouds by making use of the aerodynamic wake and some reagents.

The increasing anthropogenic effect (domestic and economic human activity) on the environment, including the atmosphere, has resulted in that more than eight kinds of clouds can now be identified as the cloud formations of anthropogenic origin (CAO). Among them there are contrails behind aircrafts,[1] helicopters,[2] and sea ships[3,4]; airdrome (stove) fogs[1]; smog (photochemical fogs)[5]; cloudy plumes over the stacks of industrial enterprises[5] and big fires, especially forest ones[6]; cloudy formations near water-cooling towers of thermal and atomic electric power plants.[5] Some spatiotemporal characteristics (STC) of the anthropogenic clouds and fogs, as well as the conditions of their formation are given in Table I.

TABLE I. Some characteristics of the anthropogenic clouds and fogs.

No.	Cloudy formation	Temperature mode	Relative humidity, %	Wind speed, m/s	Time	Size
1	Clouds behind an aircraft (contrails)	< -28°C < -36°C < -39°C	100 60 0	any	round the clock	few thousand kilometers long and up to 1 km wide
2	Cloud behind a helicopter (contrails)	< -15°C	> 85	0...3	“	area up to 1000 km^2
3	Cloud behind a sea ship (cloud tracks in wakes)	< + 32°C, including negative ones	> 70	0...5	“	up to 1000 km long and up to 50 km wide
4	Airdrome (stove) fogs	< -30°C	> 60	0...3	“	area up to 1000 km^2
5	Smog (photochemical fogs): (a) Los Angeles (b) London	 24...32°C − 1...4°C	 60...70 80...100	 calm 0...3	 noon night, morning	 “ “
6	Cloudy plumes over stacks of industrial enterprises	any temperature (negative temperatures intensify the formation)	< 100	any	round the clock	up to 100-200 km long
7	Cloud plumes of big fires, especially of the forest ones	any temperature	“	“	“	up to 5600 km long and up to 400 km wide
8	Cloudy areas near water-cooling towers	negative temperatures are favorable	70...100	0...5	“	“

N o t e . In any case anthropogenic clouds develop under the trapping layer such as inversion or isothermy.

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Analysis of the Table shows that the conditions for development of anthropogenic clouds and fogs are rather variable in air temperature (from −28°C for the contrails to +32°C for sea ship wakes and smog) and more uniform in air humidity, because clouds appear typically at enhanced humidity, except only for smog.

Having studied the CAO development conditions, one can change the probability of their appearance. Stimulation of their development may prove useful for smoothing out outdoor temperatures.

According to data from Ref. 7, artificial cirrostratus and altostratus can change the surface air temperature by 5° during half a day.

Besides, all the aforementioned CAO worsen the ecological situation[5] (for example, by oversmoking an area) and hamper observation of the Earth's surface from space.[8] This is because the appearance of such a cloudiness in daytime causes a decrease in the surface temperature and, on the contrary, prevents air cooling at nighttime.

It should be noted that physical and meteorological conditions for the development of the contrails behind an aircraft and helicopters are described in detail in Refs. 1 and 2. At the same time, only little is known about conditions for the development of cloud tracks behind sea ships (only Ref. 3 can be noted in this connection). Besides, for the first two types of cloud tracks the recommendations have been formulated how to decrease the probability of their appearance, and even the method for artificial intensification of their appearance is proposed.[9] Nothing of this sort has been proposed for cloud tracks behind sea ships (SS).

Taking into account this fact, in this paper we consider thoroughly the conditions for appearance and artificial creation of cloud tracks behind SS.

Let us first consider general physical and meteorological conditions for appearance of cloud formations of non-convective types. These are as follows:

1) the presence of a trapping layer (see the note to Table I);

2) decreased air temperature;

3) low wind speed, to the calm conditions;

4) enhanced air humidity, often close to 100% (see Table I);

5) the presence of condensation nuclei;

6) effect of mixing of air masses;

7) vertical air motions characteristic of this type of clouds.

Analyzing these conditions, we should note that the first three conditions cannot be created artificially; only the trapping layer can be destroyed, for example, by using a meteotron,[10] thus preventing the appearance of an anthropogenic cloud due to the emission of admixtures into the upper layers. The last four conditions are technically realizable.

The role of the first six conditions is generally known. Thus, there exist inversion layers without clouds with lower visibility, but non-convective clouds or fogs cannot appear without a trapping layer. Water vapor and different atmospheric admixtures, which can act as the condensation nuclei, are accumulated just under this layer. Calm or weak wind favor that accumulation. As a result, condensation or sublimation of water vapor begins. It builds up also at mixing of air masses.

The radiative cooling of the surface air, especially at night, often results in the appearance of fogs and stratus. However, air temperature in some region can be artificially decreased down to the dew point only hypothetically. In practice, it is a very expensive operation leading to condensation of water vapor on cooling elements and to air drying.

The role of hygroscopic condensation nuclei is well known[1]; and they can be introduced artificially (as well as additional moistening) together with the exhaust gases from engines.[9]

The seventh condition should be considered more attentively. It is the presence of upward flows or some circulation in a cloud. Indeed, as known,[11] particular vertical motions are inherent in every type of clouds. They provide the existence of a cloud as a whole. The spatial patterns[4] fixing artificial cloudiness formed behind ships in their aerodynamic wake confirm this fact. Under certain conditions, this cloudiness is stable enough and rather long in the horizontal direction (see Table I).

Thus, artificially induced circulation can be created in an aerodynamic wake as well. This makes it possible to stimulate creation of artificial cloud formations (ACFs) of non-convective types and to enhance their STC.

Let us consider now the results of our investigations into the problem considered. Let us first consider some results of the numerical hydro- and aerodynamic simulation of the ship model, what is necessary to determine the characteristics of the aerodynamic wake and to increase the efficiency of creation of artificial cloud formations above the sea. In simulation particular attention was paid to the role of the seventh condition in the development of clouds, namely, to creation of artificially induced circulation on the closed cycle.

It is important to note that while L.G. Kachurin[10] studied mostly the variations in thermohydrodynamic characteristics of horizontal jets in general and the aerodynamic wake in particular, we pay principal attention to the study of spatiotemporal characteristics of the intensity of the latter.

In numerical simulation, we used the plane model; and the calculations were based on the method of discrete vortices.[12] The main calculated results are presented in Fig. 1. It is seen that the aerodynamic wake is ellipse-like in its cross section and expanding with distance away form the stern. In this case, the elevation angle is $\alpha = 7°$, and the angle of horizontal expansion is $\gamma = 11°$.

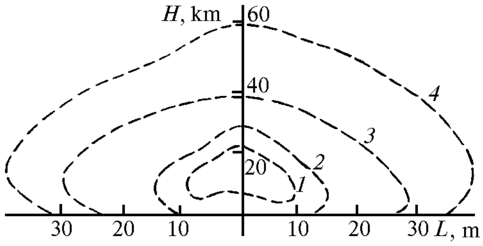

FIG. 1. Shape and dimensions of the zones of active turbulent mixing (aerodynamic wake) perpendicular to the ship longitudinal axis obtained in numerical simulation of a plane ship model at the distance from its bow: 65 *(1);* 140 *(2);* 260 *(3); and* 455 m *(4).*

The 3-D model of a ship was tested in the wind tunnel at the angles β = 0, 30, 90, and 180°. The same model was studied in the hydrochute. The vortex structure of the aerodynamic wake was better traced in the first case with the use of the vapor screen technique[12]; and the vortex axis indicated by a colored jet was better seen in the second case. This allowed us to determine the operation mode of the injectors, as well as the optimal points for their installation for injection of the reagent.

The elevation angle of the vortex wake in the wind-tunnel test was $\alpha = 11°$, and the wake expansion angle was $\gamma = 58°$. These values are greater than those obtained in numerical simulations of the plane model, what can be explained by the effect of the symmetrical deck erections. Table II presents some characteristics of the vortex zones from the data of the wind-tunnel and field experiments carried out for five different cross sections*.

Analysis of data presented in Table II shows quite good correspondence between the calculated and actual characteristics, because they are of the same order of magnitude and the values obtained in the field experiments are, as a rule, only 15–30% greater than those obtained in the wind tunnel. The only exception is the height of the vortex zone in the cross section V (on the stern) obtained in the wind-tunnel test at the angle β = 30°. The difference is 100% in this case.

TABLE II. Some characteristics of vortex zones assessed from the data of the wind tunnel (T) and field (F) experiments at the angle β = 0 *and* 30°.

Cross section	β = 0°				β = 30°			
	Height of the vortex zone, m		Vortex radius, m		Height of the vortex zone, m		Vortex radius, m	
	T	F	T	F	T	F	T	F
I	5.6	–	1.3	–	6	–	1.4	–
II	8.4	10	2.25	2.4	10	13	3	4.5
III	15.5	17	–	2.8	14.5	18	–	–
IV	17	–	–	–	14	20	–	–
V	16	–	–	–	14	28	–	–

The patterns of flowing around the model in the wind-tunnel experiment and around the ship in the field experiment coincide very closely. In both cases, the air vortex at the lee side falls down to the interface (water) and does not develop. This shows that the injectors at this side should be switched off in order to save the reagent. On the whole, the vortex flow pattern is certainly more idealized in the wind-tunnel experiment than in the field one. However, the latter is two to three orders of magnitude more expensive than the former.

The conditions for the development of the cloud zones behind SS were compared with the conditions for development of similar zones downstream of small (with diameter less than 50 km) islands[13] (the matter in this case is the orographic clouds). They turned out to be very similar. The difference is that no contribution from the products of fuel burning in ship engines is present over islands. However, the calculations performed for the six kinds of ships show that this contribution into the formation of cloud zones might be significant only at 98-% air humidity and positive temperature or 95-% humidity and negative temperature.[3]

Apart from this sufficiently direct calculation of additional moistening of the aerodynamic wake behind SS due to fuel burning, the role of the isobaric mixing of exhaust gases with the ambient air in the formation of cloud tracks behind SS was assessed. It is known that two counter directed processes may occur at such mixing: moistening, due to which the mixture approaches the saturation state, and heating, due to which the mixture goes from this state. The boundary conditions of these processes were found. According to Ref. 14, humidity of a gas mixture can be determined by the following expressions:

* The cross section I is situated at a distance of 5 m from the ship bow, the cross sections II–IV are at the distance equal to one, two, and three quarters of the ship length from the bow, respectively, and the cross section V is at the ship stern.

$$s(T) = \frac{(ls_1 - s_2)\,(T - T_2) + s_2\,(T_1 - T_2)}{(l - 1)\,(T - T_2) + (T_1 - T_2)}\,, \quad (1)$$

$$e(T) = \frac{(le_1 - e_2)\,(T - T_2) + e_2\,(T_1 - T_2)}{(l - 1)\,(T - T_2) + (T_1 - T_2)}\,, \quad (2)$$

where $l = c_{p_2}/c_{p_1}$ is the heat capacity ratio, e is the partial pressure of water vapor, and s is its mass fraction. Temperature and humidity characteristics with subscripts correspond to the mixed masses, and those without subscripts are for the mixture.

At $l = 1$ Eqs. (1) and (2) take the simpler form:

$$s(T) = \frac{\Delta s}{\Delta T}(T - T_2) + s_2 \text{ and } e(T) = \frac{\Delta e}{\Delta T}(T - T_2) + e_2. \quad (3)$$

These relationships make it possible to determine humidity from the known initial characteristics of the mixed gases at any temperature of the gas mixture T varying from T_1 to T_2. The relative humidity f is described by the expression $f = e(T)/E(T)$, where $E(T)$ is the pressure of the saturated water vapor.

If $\Delta e/\Delta T \geq \Delta e\,/\Delta T$, then tracks appear. Here the value in the left-hand side depends on the hydrogen content in fuel. The boundary of the cloud track formation is the tangent to the curve of the saturation pressure as a function of temperature.[1] Such tangents and all secants characterize processes of cloud track formation: cloud tracks appear above the tangent and do not appear below the tangent. The higher temperature of a cloud track formation behind SS in comparison with the tracks behind an aircraft and helicopters[1,2] can be explained by the fact that the gas temperature at the jet turbine engine (JTE) exit exceeds 1000°C, while the temperature at the SS exhaust pipe end is an order of magnitude less. So, for JTE $\Delta s/\Delta T = 0.0336{\cdot}10^{-3}$ (°q)$^{-1}$, and for SS this ratio is an order of magnitude greater (see curve *2* in Fig. 2). Curve *2* is plotted for the pressure $p = 1000$ hPa, and similar curves for lower pressure will lie above it up to curve *1*, which characterizes $\Delta e\,/\Delta T$ as a function of air temperature and humidity.

It follows from analysis of Fig. 2 that formation of cloud tracks behind SS may be observed at the temperature $T > 28°$ (especially as concerning the planned transition to the fuel with higher hydrogen content[15]). Injecting water into the exhaust gases or increasing the hydrogen content in them favors the formation of artificial clouds behind SS. On the contrary, cooling and drying exhaust gases decrease the probability of formation of such anthropogenic clouds.

With regard for all the aforementioned theoretical concepts, the field experiments aimed at creation of artificial cloud formations were carried out over Baltic and Black Seas in summer. The expedition group of 15 researchers headed by G.I. Mazurov supplied the hydrometeorological data for the experiment. For this purpose, the standard meteorological and aerological data were used, including weather journals and maps (surface and high-altitude ones), data of radio sounding of the atmosphere, cloud field maps, and pictures of cloudiness taken from space. The experimental results were recorded with photo and video cameras.

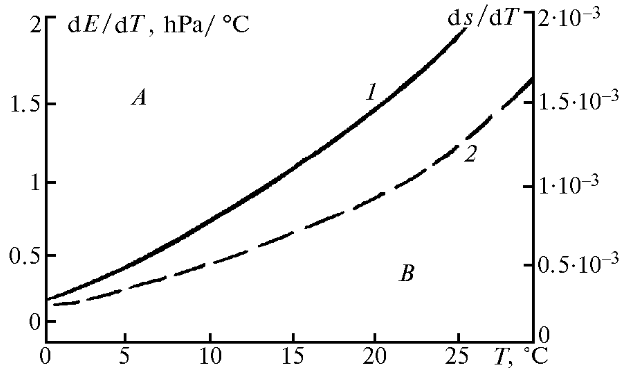

FIG. 2. Formation of cloud tracks behind SS at isobaric mixing of the exhaust gases with air as a function of air temperature and humidity and fuel properties. Zone A – clouds appear, zone B – clouds do not appear, dE/dT as a function of temperature (curve 1), ds/dT as a function of temperature (curve 2).

All the experiments were carried out in the morning and in the daytime, when the ACF created were observed visually and could be recorded from the shore and ships, as well as from an aircraft and space. The reagent was injected from the ship bow, or injectors were arranged along the ship side. The ship moved at different orientation with respect to the wind and with the speed varying from 0 (drift) to 50 km/h. All the methods of reagent injection with different arrangement of injectors on the ship and different relation between the vectors of the ship motion and wind velocity were reduced to six types. The methods, when the ship moves exactly upwind and the reagent is injected from the ship stern or bow, proved to be most promising in terms of the ACF stability.

In addition to the data of the standard meteorological observations, the data of gradient measurements up to the altitude of 8–12 m from onboard the ship were used, as well as the data of the tethered radiosonde for the altitudes up to 90 m. For the land, such data were obtained up to 300 m with the step of 10 m. The data obtained were assigned to the data of the nearest standard radiosonde that is being launched every 6 hours. Besides, the hydrological data of water temperature measurements down to the depth of 40 m were used, as well as the AT–925 and AT–850 altitude maps.

As the state of the atmospheric layer next to the water surface has the strongest effect upon the formation of ACF, particular attention was paid to the analysis of just this layer. The effect of the wind velocity on the stability of the ACF created was checked as the ship moved with the velocity of

50 km/h along a circle with the radius of 1000 m. This experiment was recorded from onboard the AN–26 aircraft flying at the altitude of 300 m. Its results confirmed the conclusion that the side wind decreases the stability of a formation created, while the contrary wind increases it due to higher velocity of air blowing around the ship and appearance of a more intense track. The circulation on the closed cycle created in it is opposed by the natural atmospheric circulation. As a result, the cloud formation moves as a whole along the leading flow.

The results of one experiment were recorded on the radar screen (Table III), and another one was recorded from the Meteor30 satellite. Judging from the evolution of the cloud image on the radar screen, it moved to the east along the leading flow with the speed of 5 m/s, and its area was 60 000 m^2 one minute after its formation, increasing up to 800 000 m^2 15 minutes later.

TABLE III. The horizontal size of the cloud on the radar screen 1, 10, and 15 minutes after its formation at different distances.

Time, min	1	10	15
Distance, m	300	3000	5400
Horizontal size, m	200 × 300	400 × 1800	800 × 1000
Area, m^2	60000	720000	800000

We have managed to take a picture of the artificially created cloud from the satellite only once, when it had flown 1 hour 55 min after the reagent injection. For the time elapsed from the formation, the cloud has shifted by 30 km to the south–west from Sevastopol under the effect of the north–east wind, what is quite real at the wind velocity of 4 m/s. At this distance it is seen in the space picture with the size of 50 × 10 km. According to the data obtained from onboard the AN–26 aircraft flying over this place, it was situated at the altitude of 200 m, under the inversion layer which was observed on the aerological diagram plotted from the radiosonde data at 9 a.m.

On the whole, the air temperature above the sea surface varied during the experiments from 12°C in Baltic Sea to 25°C in Black Sea, and the water temperature varied from 13 to 24°C, respectively. The air humidity varied from 100 to 54%, and the higher humidity was observed over Baltic Sea, while the lower one was over Black Sea. The sea roughness was similar: 2–3 in the first case and 1–2 in the second one, although the days with calm sea also occurred. Such a behavior was caused by the wind velocity. It varied from 2 to 17 m/s over Baltic Sea (mostly 8–12 m/s) and from 1 to 6 m/s over Black Sea (there was only one day when the wind velocity reached 10–12 m/s). Wind of practically all directions was observed.

According to the radiosonde data, the stable stratification such as inversions and isothermy was predominantly observed in the morning, especially in the surface layer. This thermal structure conserved held during a day independently of the wind velocity. The atmospheric pressure varied from 1025 hPa over Baltic Sea to 997 hPa near Sevastopol. As for weather phenomena, only haze with the visibility range more than 4 km and rain over Baltic Sea were observed.

The more complicated weather conditions and turbulent state of the atmosphere over Baltic Sea have caused the results of the experiments obtained there. The mean values of STC of the cloud formations created near Baltiisk and Sevastopol are presented in Table IV. Analysis of these data shows that in the latter case they are 1.5 times longer in the length and lifetime, 1.2 times thicker, and 10 times wider. In this statistics, the anomalously big cloud observed once from space was excluded from the consideration.

TABLE IV. Mean STC of the cloud formations created in the field experiments over Baltic and Black Seas.

Region of the experiment	Length, m	Thickness, m	Width, m	Lifetime, min
Baltic Sea	800	150	50	8
Black Sea	1300	180	530	13
Taking into account the extreme case observed from satellite	53500	180	1320	20

Thus, the field experiments over the seas have shown that the following factors principally affect STC of the cloud formations created using SS:

1) Stratification of the lower part of the atmospheric boundary layer (stable stratification favors the increase of STC, and unstable one favors its decrease);

2) The direction of the ship motion relative to the wind (β) and its speed. Creation of ACF is most efficient when a ship moves upwind ($\beta = 0$). This effect can even exceed for a while the influence of instability in the atmospheric boundary layer. STC decrease at the side ($\beta > 0$) and especially fair wind;

3) The wind velocity in the area of the field experiment. It has the double effect. The wind less than 2 m/s and the turbulence connected with it favor conservation of ACF, and it spreads slowly. The wind speed more than 5–6 m/s at upwind motion of a ship favors creation of a thick wake and increases the ACF stability, but the turbulence connected with it quickly spreads the cloud, especially at the side wind.

Besides, we have revealed that, contrary to the expectations, the effect of relative humidity on STC is not observed. It can be explained by the fact that the cloud is of aerosol nature and the injected reagent is not hygroscopic. Another explanation may be the significant effect of moisture entraining from the water surface due to the strong induced turbulence.

The absolute values of such weather characteristics as the atmospheric pressure, air and water temperature did not affect the cloud formation, at least due to their small variations.

The elevation angle of a cloud in the field experiments varied by an order of magnitude from 3 to 31° depending on the incoming flow velocity and stratification of the surface layer. It was 11° in the wind tunnel at the wind velocity of 26 m/s that is greater than the velocity of the incoming flow relative to the ship.

On the whole, the results of the field and laboratory experiments coincide both in the type of circulation and in its intensity. The strongest effect on creation of ACF is reached as a ship moves upwind with the maximum speed. At the side wind, a cloud at the lee side falls down to the water surface and does not develop. If a cloud has been created in the ship drift, it develops along the vertical direction with unstable lifetime.

The results of the field experiments closely correspond to the results of the numerical simulation which gave the elevation angle $\alpha = 7°$ ($\alpha = 0.1$). However, the horizontal divergence angle of a vortex is $\gamma = 11°$. This may be caused by the consideration of the plane model of a ship (without deck erections).

In conclusion, it should be noted that to decrease the probability of appearance of artificial cloud formations behind a sea ship, it should change the direction of its motion relative to the wind in such a way that the wind becomes blowing from side. Besides, exhaust gases may be dried what brings them into the state far from saturation. It may be achieved by the use of different filters and cleaners.

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