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DISPERSION PATTERNS OF AEROSOL PARTICLES IN A FREE ATMOSPHERE

by

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

DISPERSION PATTERNS OF AEROSOL PARTICLES IN A FREE ATMOSPHERE

G. M. Petrova and A. N. Miroshkina

The dispersion of solid particles of irregular shape, 100-1000 um in diameter, from heights of 500-8000 m, and spheric particles, 30-100 μm in diameter, from heights of 500-1000 m was investigated in a free atmosphere.

Sand and plastic luminescent particles were used as indicators. The distribution pattern of the particles on the earth's surface was studied. Empirical formulas, enabling one to calculate the surface particle density, falling from an instantaneous point source, with their assigned dispersion according to fallout rates, depending upon the height of location of the source and the average speed of the wind, are given. An evaluation of the dispersion fallout of coefficients in an atmosphere of a mixture of K_y and K_z is given.

Introduction

In this work the results of experimental investigations of the dispersion of solid particles from a source located in a free atmosphere are examined. The dispersion of particles in an atmosphere is of considerable practical interest. Thus, for example, the dusting of agricultural crops in order to eliminate pests or plant diseases is performed by aircraft by dispersing a suitable material. In similar vein, there is sanitary treatment of reservoirs to prevent the spread of the anopheline mosquito, the introduction of

microfertilizers, the dusting of forests in controlling ticks – carriers of encephalitis and forest pests, etc.

At present the spraying with aerosols is conducted from a low altitude and during a slight wind. As a rule, the released powders are polydispersional, associated with the fact that a considerable part of the substance in the form of very fine particles is carried great distances and falls beyond the boundary of the treated territory.

Knowledge of the dispersion patterns of various materials in an atmosphere would make it possible to use the aerosol method more effectively in solving many national-economic problems.

The movement of particles, ejected in the atmosphere depends on many factors. It consists of their regulated transfer by the wind, as a result of which the entire mass of particles shifts in direction and at the speed of the average wind;[1] it also involves the fallout under gravity and dispersion due to variability of air currents not regulated by atmospheric movements the result of which the volume particle density decreases, and the average distances between them and the overall dimensions of the cloud of particles increases. Any increase in the dimensions of the initially released cloud in some direction promotes its further dispersion in connection with the fact that such an increase in dimension gives rise to fluctuations in the speed of the wind and temperature of an even greater scale.

The immediate problem of this work involved experimental investigations of the fallout and dispersion of particles in an atmosphere at scales of interest in practical use. A wide range of particles sizes, characterized by speeds of fall from 0.1 to 3 m/s was selected for the investigations. Each experiment involved a certain quantity of particles being released from an aircraft at a predesignated point. The area of expected fallout of particles was

[1]Let us agree to call "average wind" that wind produced by a speed and direction which is a vector averaged vertically between the point of release and the earth's surface.

covered by a network of sticky plane tables. Upon completion of the experiment, the plane tables were collected, the ultraviolet illumination during fallout of the particles on the tables was calculated; for identification, the particles were colored beforehand with luminophors. As a result it was possible to reconstruct the distribution pattern of falling particles on the earth's surface. Releases were made at heights from several hundred meters to 5 km. The area, in which noticeable surface particle density was detected attained several thousand square kilometers.

The analysis of materials had as an aim, to reveal the connection between basic characteristics of the trail – on the one hand, the value of surface particle density in the fallout zone, the location of the zone of maximum concentration, the value of the dispersion of the surface concentration, and – on the other hand, the total amount of ejected particles, the speed of the wind and the fall rate of particles in the atmosphere.

As a result simple empirical dependences, which can be used in solving many practical problems were obtained. Furthermore, an attempt was made to evaluate the coefficients of turbulent dispersion of a pollutant in a free atmosphere.

Methodology

Preparation of luminescent sand particles. The material for the investigation of the dispersion of heavy particles (speed of fallout of more than 1 m/s) was natural quartz sand with a specific gravity, on the average, of 2.6 g/cm^3, whose typical particle size distribution is presented in Table 1.

Table 1.

Diameter (μm)	125–175	175–225	225–275	275–325	325–375	375–425	425–475	475–525	525–575	575–625	625–675
Quantity (%)	2,9	13,5	35,1	18,5	11,9	9,0	3,5	2,5	1,4	0,9	0,8

The sand was dispersed into fractions with the help of a vibrating screen with calibrated brass grids. As a result of screening fractions with narrower size ranges were obtained. As an example, fractions, designated as P-250 and P-350 are given in Table 2.

Table 2.

Diameter (μm)		175—225	225—275	275—325	325—375	375—425	425—475	475—525
Quantity (%)	Fraction P-250	10	50	26	10	3	1	0
	Fraction P-350	0	2	13	46	31	7	1

For facilitating the counting of particles the dispersed sand was colored with luminophors, released by industry under the brands: "light-yellow lyumogen" and "water-blue lyumogen." A quantity of 50 g lyumogen per 100 kg sand was the accepted rate for calculations. The color of the sand in the first experiments (1955-56) was performed using agar-agar as a binding substance between the sand and the dye by a method proposed by the Institute of Organic Chemistry of the Academy of Sciences, USSR [5], and then without using agar-agar. The last method of dyeing, the so-called "dry" method, was developed at the Institute of Applied Geophysics and was first used in experiments in 1958.

Laboratory experiments and field tests showed that the "dry" method gave a good uniform coloring. Lyumogen is held firmly on the particles, and even for prolonged periods in water, does not change the luminous intensity. The advantage of the "dry" method is the much shorter (by 8-10 times) time of preparation of the material. After dyeing the sand was subjected to secondary screening. It should be noted that the sand, colored by water-blue lyumogen, after a prolonged period in the sun, partially lost its ability to fluoresce.

Preparation of luminescent particles made of plastic. For light (speed of fallout less than 1 m/s) use, particles were obtained

by the polymerization of an emulsion of a methyl ether of methacrylic acid in water with additions of a catalyst and an emulsifier. In experiments with particles less than 100 μm in diameter polymethyl methacrylate powder produced at the Kharkov Plant of Dental Materials (KhZZM) was used. This polydisperse (from 5 to 100 μm) is a powder; its particles have a regular spheric form and are well stained in an alcohol solution by luminescent dyes. The specific weight of the particles of the emulsified polymethyl methacrylate powder is 1.12-1.16 g/cm^3. The powder was screened into separate fractions with limits of 10-45, 45-65, 65-80 and 80-100 μm.

In experiments demanding larger particles, a powder, produced at the "Carbolite" (Orekh-Zuyevo) Plant was used. Here, the fractions were separated into 125-150, 150-200, 200-250 and 250-315 μm.

The sieving of the powders was done on vibrating screens. In Table 3 the distribution of the particles of powder by size for the fraction 10-45 and 45-65 μm is shown.

Table 3.

Diameter (μm)		<15±7,5	30±7,5	45±7,5	60±7,5	75±7,5
Quantity (%)	Fraction 10-45	22	44	32	2	0
	Fraction 45-65	3	8	53	34	2

The method of coloring the particles of the powder of methyl ether of methacrylic acid was supplied by A. B. Davankov [2]. A large number of dyes (24) was investigated in the laboratory. However, in preparing large quantities of powder, only those which give the most intense luminescence (Table 4) were used.

Table 4.

Designation of dye	Color of luminescence
Rhodamine S	Red
Rhodamine 6Zh	Orange
Auramine	Yellow
Eosin	Orange-pink

The dyeing of the powder was done in an alcohol solution. By laboratory experiments were determined the norm of dyeing – for 1 kg of powder 10 g of dye dissolved in 1.25 ℓ alcohol was required. When dyeing with rhodamine 6Zh the quantity of dye was increased to 15 g. Upon completion of dyeing the remaining alcohol was drawn off by a suction filter and the powder was washed with water until a colorless filtrate was obtained and was dried on special stands at a temperature of 30-35°C [1]. When using colored powders as aerosols the stability of the dye to solar radiation is important. An experimental check showed that all the rhodamine was sufficiently stable. Auramine turned out to be less stable.

Release of particles. The release of the colored powder and sand was done from aircraft of different types with the help of devices of different systems. The systems and techniques of release were selected of such design, so that the source of the particles was, as far as possible, instantaneous and pinpointed. However, even in this case, in initial moment a cloud extended in the direction of movement of the aircraft, and the length of the cloud was 100-200 m. With respect to the length of the spot formed on earth – "the trail," this value is very small (nearly 0.1 in experiments with sand and 0.01 – with plastic) which permits pinpointing the source with a sufficiently good approximation.

For operations in sparsely populated regions (the experiments of 1956) for releasing sand from an aircraft specially made canisters equipped with a parachute were used. At the instant of opening of the parachute the canister was opened and the sand dumped for 1-2 s, and the empty canister was lowered in the parachute. The opening of the canister occurred 1 s after its release from the aircraft. Special attachments made it possible to release from 2-4 canisters simultaneously, the capacity of each was 150-200 kg.

For releasing particles over populated regions (experiments of 1957-1960) a special cassette with a capacity of 200-250 kg of sand 200-300 μm of size fraction or 100 kg of plastic particles was used. The release time of powders from the cassette was 1-2 s.

Description of the test site. The recovery of released particles was made on a previously prepared test site, on which plywood plane tables were laid out in a specified order. The dimensions of the test sites were selected depending upon the scale of the experiments. In experiments with particles of sand the area of the test sites were 20 to 225 km^2, in experiments with light particles – from 3 to 10 thousand km^2.

The 1955 test site consisted of a small (4 km × 5 km) and a large (8 km × 10 km) site. Its axial line was oriented along an azimuth of 150°, perpendicular to axes intersecting 17 boundaries and at a certain angle to four roads. The orientation of the test site was selected such that in the region of the test site in August northwest and western currents predominate in lower part of troposphere based on many years of records. In the territory of the small site the boundaries were crossed in 500 m; the plane tables were laid out along the boundaries and on an axis at every 50 m.

At the large site the boundaries were crossed at 1 km; the plane tables were laid out at every 100 m.

The area of the 1956 test sites, located in the Uzbek Soviet Socialist Republic, was 5 km ×.5 km (the small test site) and 15 km × × 15 km (the large test site). The small test site was bisected by the lower reaches of the Fergana Valley. It is represented by an even rectangular site, overgrown by low (5-10 cm) grass. All of the territory of the test site was bisected by regular rectangles with sides, 500 and 250 m, along which plane tables were laid out every 50 m. The large test site was in the center of the Hungry steppe. The site here is smooth, covered by grass 10-20 cm tall. Part of the test site (4 × 6) km^2 consisted of a ploughed field. Throughout the territory of the large test site plane tables were spread every 100 m along straight lines, extending 1 km in a north-south direction.

In working with light particles (speed of fall of which is 0.07 to 0.8 m/s) the area of the test sites was 50 km × 75 km and 100 km × 100 km. The first experiments (1957) with particles of

plastic, from 10 to 300 μm in diameter were conducted in the territory of Moscow and Kaluga Oblasts. Here the test site was bisected (Fig. 1) into an area nearly 6500 km^2, in which nine routes were layed ensuring as far as possible the uniform distribution of plane tables. The extent of each route was 350-400 km. Forests and fields were located in the territory of the test site. Relief of the site was sufficiently smooth, weakly dissected by the valleys of small streams. The plane tables were arranged in the open places every 1-2 km.

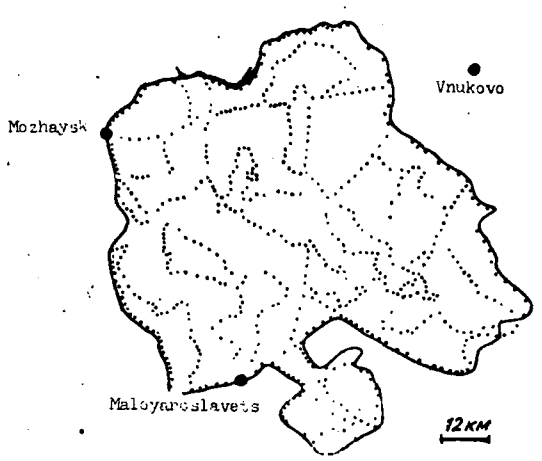

Fig. 1. Layout of the 1957 test site.

Subsequent experiments (1959-60) with particles of plastic 10-80 μm in diameter were conducted on the experimental meteorological test site area, 75 km × 50 km, of the Ukrainian Scientific Research Hydrometeorological Institute, located in the south of Dnepropetrovsk Oblast. The site here is a plain, weakly dissected; almost all of the territory of the test site constitutes an agricultural region, and the industrial region of Krivoy Rog is located only in its western part. In the territory of the test site there were 160 observation points located in villages at a distance of 3-10 km one from another. In 1960, the territories of the test site were increased to 100 km × 100 km. Within the new borders of the test site encompassed the western part of Dnepropetrovk, the extreme northern part of Kherson and the southern part of Kirovo Oblasts. The number of observation posts was increased to 360. In central

part of the test site observation posts were arranged every 3-5 km, and on the periphery – every 7-10 km. In the center of the test site within a radius of 20 km observation network was made denser such that the plane tables were arranged every 2 km.

Plywood plane tables, with a surface area of 0.02 and 0.12 m^2 were used to recover the particles. Tracing paper, covered with a sticky lubricant, consisting of a mixture of rosin and castor oil in the proportion 2:3 was glued on the plywood. Such a mixture does not soak into the tracing paper and remains sticky for several months on the plane tables.

Miscounting of tests. Primary treatment of tests consisted of the determination of the amount of fallout of particles on the plane tables and the determination of the size of these particles. The quantity of particles was calculated visually during the illumination of the plane table by ultraviolet radiation. Used in the laboratory treatment were table model illuminators, having three L-33 luminescent tubes with filters made of brand UFS-4 uviol glass.

In addition, illuminators with SVDSh-250 and SVD-120 tubes were also used.

The error in counting large particles amounted to 5-10%. Particles less than 100 μm poorly visible to the naked eye, in this case counting were handled with a 4× or 5× magnifier (with a control check). The diameter of the particles was determined with the aid of a microscope.

Methodology of aerological observations. Aerological observations during the period of experimentation were conducted, first, for the purpose of determining the profile of the wind, without which the experiment could not be established and, secondly, for obtaining the characteristics of the atmospheric composition during the period of experimentation.

The direction and speed of wind with altitude were measured by the monopoint pilot balloon method. The pilot balloon observations

commenced, as a rule, for 1-2 hours prior to recovery and were conducted during the entire period of fallout of particles with an interval of 30-60 minutes between releases. The point of pilot balloon observations in carrying out the experiments in 1956, 1959 and 1960 was located near the center of the test site. In 1957, the wind sounding was conducted at the Mozhaysk, Vnukovo and, Maloyaroslavet stations located on the border of the test site, within 50 km of its center (Fig. 1). Pilot balloons were released every hour during the period set on the day before the experiment.

The determination of the vertical distribution of temperature was performed by the standard method of aircraft sounding of the atmosphere prior to release and after the release of particles. In 1959, the results of aircraft ascents at the Dnepropetrovsk station or reports of radiosondes at the Krivoy Rog station were used for obtaining data on the vertical profile of temperature.

Results of the Experiments

An analysis of results of aerological observations. One of the important meteorological parameters in the propagation of particles in a free atmosphere is the speed and direction of the average wind in a given stratum.

The analysis of experimental results showed that the fallout of particles from a point source occurs in the direction of the average wind, measured during the period of the experiment in the layer of fallout of particles. Average wind was calculated according to a profile of the wind by means of a geometric summation of the separate vectors of the wind at every level.

$$\vec{u} = \frac{1}{H}\sum_{i=1}^{n}\vec{u}_i \Delta z_i,$$

where H – height of the release of particles, u_i – vector of wind in the layer Δz_i, n – number of layers.

Direction and speed of the average wind during the experiment was sufficiently stable. In most cases the average wind changed by not more than 10° in direction and by not more than 1 m/s in speed. In rare cases this change amounted to 20°, 2-3 m/s. For clarity, in Tables 5 and 6 the values of average wind troughout the periods of observations for several experiments are given.

Table 5.

Late	Time of release (hour, minutes)	H (м)	Period of observations (hour, minutes)	Average wind	
				Direction (degree)	Speed (m/s)
22. IX/1959	10 23	1000	10 00 10 35 11 35 12 35	322 316 302 282	3,7 3,3 3,8 3,2
23. X/1959	13 05	300	12 45 13 35 14 02 15 00	239 258 257 258	5,5 6,7 7,2 6,0
4. IX/1960	12 26	1000	12 07 12 50 13 31 14 09 15 06	256 255 257 263 263	4,6 4,0 4,8 5,6 4,0
5. IX/1960	12 13	1000	12 11 12 52 14 02 15 03 16 00	190 185 171 176 177	5,8 6,2 5,0 5,4 7,2
11. IX/1960	13 30	1500	13 35 14 27 15 35 16 34	299 308 301 297	4,7 3,6 5,0 4,2
12. IX/1960	12 06	1000	12 03 13 05 14 11 15 02	281 285 299 303	5,1 5 4 3,6 3,8

The vertical profile of the vector of wind in most cases was uniform, without sharply expressed changes. Fluctuations in direction and wind speed in one or another side within the entire layer of propagation of particles were within the limits of 10-20° and 1-2 m/s.

Mean values of wind speed during the experiments are given in the combined Table 7. As shown in the table, the experiments were

Table 6.

Date	Name of station	Periods of observations (hour, minutes)													
		9 00		10 00		11 00		12 00		13 00		14 00		15 00	
		φ	u	φ	u	φ	u	φ	u	φ	u	φ	u	φ	u
26. VII/1957	Malo-yaro-slavets, Vnukovo	132	11,9	136 144	10,3 12,2	133 144	8,6 10,9	141 134	9,1 10,3	129 136	8,0 9,7				
22. VIII/1957	Malo-yaro-slavets, Vnukovo			212	6,0	204 211	5,8 5,7	202 209	6,2 5,5	213 208	7,4 5,6	201 201	8,1 5,9	194	8,4

Note. φ - in degrees, u - in m/s.

conducted with a wind of 2-15 m/s. Cases of weak wind ($u < 2$ m/s) were excluded from further consideration.

As it is known, temperature stratification of the atmosphere is one of important characteristics, making it possible to determine the degree of stability of the atmosphere. Results of aircraft sounding showed that the atmosphere with altitude in all cases, aside from experiments 10, 15, 24, and 38, is stratified uniformly; the gradient throughout all altitudes does not change in sign. Calculated according to a profile of the temperature the average vertical gradients of temperature γ in the layer of the fallout of particles are given in Table 7. In cases with inversion, the gradient γ is calculated in the layer lower than the inversion (experiments 15, 24, 38), and in experiment 10 – higher than the inversion layer. In column 11 of this table the gradients of temperature in the lower 100 m layer of the atmosphere (γ_{100}) are given, where the temperature stratification is more sharply expressed.

An analysis of temperature profiles makes it possible to separate three basic types of stratification of the examined layer of atmosphere taking place during the experiments.

Type I – the lability energy is positive throughout the examined layer (vertical gradient of temperature γ in the lower part of the layer is more than 1°/100 m, and higher than the superadiabatic or approximate equilibrium gradients).

Table 7.

No. of trace	No. of experiment	Date of experiment	Time of release (hour, min.)	Initial data of the experiments								Results of experiments				
				H	D μ	w	Q	u	γ	γ_{100}	Type of stratification	x_{max}	q_{max}	σ_y	σ_x	$x_{кнн}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1	29. III/1956	11 14	500	250	1,35	$1,8\cdot10^{9}$	15				$5,7\cdot10^{3}$	$6,2\cdot10^{3}$	$5,8\cdot10^{1}$	$7,4\cdot10^{2}$	$5,6\cdot10^{3}$
2					300	1,55	$9,5\cdot10^{8}$					$5,1\cdot10^{3}$	$1,4\cdot10^{3}$	$5,9\cdot10^{1}$	$6,2\cdot10^{2}$	$4,8\cdot10^{3}$
3					350	1,80	$3,5\cdot10^{8}$					$4,9\cdot10^{3}$	$9,2\cdot10^{3}$	$2,6\cdot10^{1}$	$4,6\cdot10^{2}$	$4,2\cdot10^{3}$
4	2	11. IV/1956	8 07	1000	250	1,35	$1,8\cdot10^{9}$	5	0,7		III	$4,1\cdot10^{3}$	$1,0\cdot10^{4}$	$3,0\cdot10^{1}$	$6,4\cdot10^{2}$	$3,7\cdot10^{3}$
5					300	1,55	$9,5\cdot10^{8}$					$3,6\cdot10^{3}$	$2,8\cdot10^{3}$	$2,8\cdot10^{1}$	$4,4\cdot10^{2}$	$3,2\cdot10^{3}$
6					350	1,80	$3,5\cdot10^{8}$					$3,4\cdot10^{3}$	$3,4\cdot10^{3}$	$2,5\cdot10^{1}$	$4,4\cdot10^{2}$	$2,8\cdot10^{3}$
7	3	14. IV/1956	5 35	500	200	1,10	$1,8\cdot10^{8}$	4				$1,7\cdot10^{3}$	$3,0\cdot10^{3}$	$3,0\cdot10^{1}$	$3,5\cdot10^{2}$	$1,8\cdot10^{3}$
8					250	1,35	$9,5\cdot10^{8}$					$1,5\cdot10^{3}$	$2,6\cdot10^{4}$	$2,2\cdot10^{1}$	$3,1\cdot10^{2}$	$1,5\cdot10^{3}$
9					300	1,55	$6,1\cdot10^{8}$					$1,4\cdot10^{3}$	$5,0\cdot10^{4}$	$2,0\cdot10^{1}$	$2,2\cdot10^{2}$	$1,3\cdot10^{3}$
10					350	1,80	$6,2\cdot10^{8}$					$1,2\cdot10^{3}$	$2,3\cdot10^{4}$	$2,0\cdot10^{1}$	$1,2\cdot10^{2}$	$1,1\cdot10^{3}$
11	4	14. IV/1956	15 07	1000	250	1,35	$9,5\cdot10^{8}$	3				$2,1\cdot10^{3}$	$1,8\cdot10^{4}$	$3,1\cdot10^{1}$	$2,6\cdot10^{2}$	$2,2\cdot10^{3}$
12					300	1,55	$6,1\cdot10^{8}$					$1,9\cdot10^{3}$	$1,6\cdot10^{4}$	$2,2\cdot10^{1}$	$2,5\cdot10^{2}$	$1,9\cdot10^{3}$
13					350	1,80	$6,2\cdot10^{8}$					$1,7\cdot10^{3}$	$1,1\cdot10^{4}$	$3,1\cdot10^{1}$	$2,2\cdot10^{2}$	$1,7\cdot10^{3}$
14	5	18. IV/1956	5 27	1000	200	1,10	$2,8\cdot10^{8}$	3				$1,8\cdot10^{3}$	$9,5\cdot10^{3}$	$1,8\cdot10^{1}$	$2,8\cdot10^{2}$	$2,7\cdot10^{3}$
15					250	1,35	$1,2\cdot10^{9}$					$1,6\cdot10^{3}$	$4,7\cdot10^{4}$	$2,5\cdot10^{1}$	$2,2\cdot10^{2}$	$2,2\cdot10^{3}$
16					300	1,55	$5,1\cdot10^{8}$					$1,5\cdot10^{3}$	$4,0\cdot10^{4}$	$1,6\cdot10^{1}$	$1,8\cdot10^{2}$	$1,9\cdot10^{3}$
17					350	1,80	$5,8\cdot10^{8}$					$1,3\cdot10^{3}$	$5,5\cdot10^{4}$	$1,5\cdot10^{1}$	$1,2\cdot10^{2}$	$1,7\cdot10^{3}$
18					400	2,00	$3,5\cdot10^{8}$					$1,2\cdot10^{3}$	$5,3\cdot10^{4}$	$1,2\cdot10^{1}$	$6,6\cdot10^{2}$	$1,5\cdot10^{3}$
19	6	21. IV/1956	5 32	1000	250	1,35	$1,2\cdot10^{9}$	4				$2,9\cdot10^{3}$	$1,6\cdot10^{4}$	$3,0\cdot10^{1}$	$4,8\cdot10^{2}$	$3,0\cdot10^{3}$
20					300	1,55	$5,0\cdot10^{8}$					$2,5\cdot10^{3}$	$1,6\cdot10^{4}$	$2,2\cdot10^{1}$	$4,2\cdot10^{2}$	$2,6\cdot10^{3}$
21					350	1,80	$6,5\cdot10^{8}$					$2,3\cdot10^{3}$	$1,6\cdot10^{4}$	$2,0\cdot10^{1}$	$3,5\cdot10^{2}$	$2,2\cdot10^{3}$
22					400	2,00	$3,2\cdot10^{8}$					$2,0\cdot10^{3}$	$1,2\cdot10^{4}$	$2,4\cdot10^{1}$	$2,4\cdot10^{2}$	$2,0\cdot10^{3}$
23	7	21. IV/1956	10 15	1000	200	1,10	$1,6\cdot10^{8}$	4	0,9		III	$3,6\cdot10^{3}$	$5,2\cdot10^{3}$	$4,5\cdot10^{1}$	$2,4\cdot10^{2}$	$3,6\cdot10^{3}$
24					250	1,35	$1,2\cdot10^{9}$					$3,2\cdot10^{3}$	$2,8\cdot10^{4}$	$2,1\cdot10^{1}$	$3,4\cdot10^{2}$	$3,0\cdot10^{3}$
25					300	1,55	$5,0\cdot10^{8}$					$3,0\cdot10^{3}$	$1,6\cdot10^{4}$	$3,5\cdot10^{1}$	$3,5\cdot10^{2}$	$2,6\cdot10^{3}$
26					350	1,80	$6,5\cdot10^{8}$					$2,5\cdot10^{3}$	$2,3\cdot10^{4}$	$3,0\cdot10^{1}$	$2,6\cdot10^{2}$	$2,2\cdot10^{3}$
27					400	2,00	$3,2\cdot10^{8}$					$2,4\cdot10^{3}$	$1,4\cdot10^{4}$	$3,5\cdot10^{1}$	$2,3\cdot10^{2}$	$2,0\cdot10^{3}$
28	8	26. IV/1956	10 22	1000	400	2,00	$1,6\cdot10^{8}$	10				$3,5\cdot10^{3}$	$1,6\cdot10^{3}$	$2,5\cdot10^{1}$	$2,3\cdot10^{2}$	$5,0\cdot10^{3}$
29					450	2,20	$3,1\cdot10^{8}$					$3,5\cdot10^{3}$	$3,2\cdot10^{3}$	$2,6\cdot10^{1}$	$2,1\cdot10^{2}$	$4,5\cdot10^{3}$
30	9	26. IV/1956	11 08	1000	400	2,00	$1,6\cdot10^{8}$	6				$3,2\cdot10^{3}$	$7,0\cdot10^{2}$	$2,8\cdot10^{1}$	$3,2\cdot10^{2}$	$3,0\cdot10^{3}$
31					450	2,20	$3,1\cdot10^{8}$					$3,0\cdot10^{3}$	$1,2\cdot10^{3}$	$3,8\cdot10^{1}$	$2,3\cdot10^{2}$	$2,7\cdot10^{3}$
32					500	2,40	$1,0\cdot10^{8}$					$2,9\cdot10^{3}$	$4,8\cdot10^{3}$	$2,8\cdot10^{1}$	$2,2\cdot10^{2}$	$2,5\cdot10^{3}$

Table 7. (Cont'd)

No. of trace	No. of experiment	Date of experiment	Time of release (hour, min.)	Initial data of the experiments								Results of experiments				
				Ψ	D μ	w	Q	u	γ	γ_{100}	Type of stratification	x_{max}	q_{max}	σ_y	σ_x	x_{max}
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
33 34 35	10	4. V/1956	6 38	4000	300 350 400	1,55 1,80 2,00	$8,3\cdot10^8$ $3,0\cdot10^9$ $2,0\cdot10^9$	5	0,6		IV	$1,15\cdot10^4$ $1,06\cdot10^4$ $1,02\cdot10^4$	$6,2\cdot10^2$ $7,5\cdot10^2$ $9,3\cdot10^2$	$1,3\cdot10^2$ $1,8\cdot10^2$ $1,2\cdot10^2$	$1,56\cdot10^3$ $1,24\cdot10^3$ $1,32\cdot10^3$	$1,29\cdot10^4$ $1,11\cdot10^4$ $1,0\cdot10^4$
36 37 38	11	5. V/1956	7 04	4000	250 300 350	1,35 1,55 1,80	$6,6\cdot10^9$ $3,4\cdot10^9$ $1,3\cdot10^9$	5	0,7		III	$1,67\cdot10^4$ $1,59\cdot10^4$ $1,40\cdot10^4$	$1,3\cdot10^3$ $9,8\cdot10^2$ $9,0\cdot10^2$	$1,4\cdot10^2$ $1,8\cdot10^2$ $1,4\cdot10^2$	$2,94\cdot10^3$ $2,90\cdot10^3$ $2,31\cdot10^3$	$1,48\cdot10^4$ $1,29\cdot10^4$ $1,11\cdot10^4$
39 40	12	10. V/1956	9 44	4000	500 550	2,40 2,65	$6,7\cdot10^8$ $5,8\cdot10^8$	6				$8,4\cdot10^3$ $7,2\cdot10^3$	$4,1\cdot10^2$ $5,0\cdot10^2$	$1,2\cdot10^2$ $8,5\cdot10^1$	$1,34\cdot10^3$ $9,62\cdot10^2$	$1,0\cdot10^4$ $9,1\cdot10^3$
41 42 43	13	15. V/1956	11 26	8000	400 450 500	2,00 2,20 2,40		5				$1,86\cdot10^4$ $1,76\cdot10^4$ $1,77\cdot10^4$	$5,0\cdot10^2$ $6,0\cdot10^2$ $9,0\cdot10^2$	$2,3\cdot10^2$ $2,3\cdot10^2$ $1,8\cdot10^2$	$2,3\cdot10^3$ $1,70\cdot10^3$ $1,54\cdot10^3$	$2,00\cdot10^4$ $1,82\cdot10^4$ $1,67\cdot10^4$
44	14	16. V/1956	8 36	7000	500	2,40		6				$1,40\cdot10^4$	$2,4\cdot10^3$	$1,6\cdot10^2$	$2,3\cdot10^3$	$1,75\cdot10^4$
45 46	15	20. VI/1957	18 02	4000	225 250	0,86 0,98	$7,8\cdot10^8$ $3,2\cdot10^9$	10	0,8	1,4	IV	$4,10\cdot10^4$ $4,20\cdot10^4$	$6,0\cdot10^1$ $2,3\cdot10^2$	— —	$6,2\cdot10^3$ $7,0\cdot10^3$	$4,6\cdot10^4$ $4,1\cdot10^4$
47	15	20. IV.1957	18 02	4000	275	1,10	$2,0\cdot10^9$	10	0,8	1,4	IV	$3,81\cdot10^4$	$3,0\cdot10^1$	—	$6,0\cdot10^3$	$3,6\cdot10^4$
48 49 50	16	02. VII/1957	11 55	5000	150 175 200	0,50 0,62 0,74	$6,6\cdot10^9$ $1,4\cdot10^{10}$ $6,2\cdot10^9$	9	0,6	1,0	III	$6,70\cdot10^4$ $6,50\cdot10^4$ $6,50\cdot10^4$	$5,0\cdot10^1$ $1,4\cdot10^2$ $1,0\cdot10^2$	$1,4\cdot10^3$ $1,6\cdot10^3$ $1,3\cdot10^3$	$1,28\cdot10^4$ $1,50\cdot10^4$ $1,58\cdot10^4$	$9,0\cdot10^4$ $7,3\cdot10^4$ $6,1\cdot10^4$
51 52 53	17	15. VII/1957	10 50	2000	75 100 125	0,15 0,25 0,37	$2,1\cdot10^{10}$ $8,7\cdot10^{10}$ $2,9\cdot10^{10}$	9	0,8	1,4	II	$8,20\cdot10^4$ $5,40\cdot10^4$ $4,70\cdot10^4$	$5,0\cdot10^1$ $3,6\cdot10^2$ $2,0\cdot10^2$	$3,7\cdot10^3$ $1,5\cdot10^3$ $2,1\cdot10^3$	$2,13\cdot10^4$ $1,73\cdot10^4$ $1,93\cdot10^4$	$12\cdot10^4$ $7,2\cdot10^4$ $4,9\cdot10^4$
54 55 56	18	26. VII/1957	9 44	2000	75 90 105	0,15 0,22 0,27	$9,0\cdot10^{10}$ $6,7\cdot10^{10}$ $2,8\cdot10^{10}$	10	0,6	0,2	III	$7,70\cdot10^4$ $6,70\cdot10^4$ $7,0\cdot10^4$	$3,0\cdot10^2$ $1,6\cdot10^2$ $8,0\cdot10^1$	— — —	$2,0\cdot10^4$ $1,28\cdot10^4$ $1,28\cdot10^4$	$13,3\cdot10^4$ $9,1\cdot10^4$ $7,4\cdot10^4$
57	19	15. VIII/1957	12 43	2000	10—60	0,07	$1,2\cdot10^{12}$	2	0,8	1,7	II	$2,40\cdot10^4$	$2,1\cdot10^3$	$1,2\cdot10^3$	$4,8\cdot10^3$	$5,7\cdot10^4$
58	20	22. VIII/1957	10 49	2000	10—60	0,07	$2,0\cdot10^{12}$	6	0,6	1,0	III	$3,30\cdot10^4$	$1,5\cdot10^3$	$1,6\cdot10^3$	$5,4\cdot10^3$	$17,1\cdot10^4$
59	21	11. X/1958	3 30	150	45—65	0,12	$5,2\cdot10^{11}$	6				$1,5\cdot10^3$	$4,2\cdot10^5$	$1,2\cdot10^2$	$9,0\cdot10^1$	$6,67\cdot10^3$
60	22	22. IX/1959	10 23	1000	10—65	0,07	$6,6\cdot10^{11}$	4				$1,70\cdot10^4$	$2,1\cdot10^3$	$1,8\cdot10^3$	$7,8\cdot10^3$	$5,7\cdot10^4$

Table 7. (Cont'd)

No. of trace	No. of experiment	Date of experiment	Time of release (hour, min.)	Initial data of the experiments								Results of experiments				
				H	D / μ	w	Q	u	γ	γ_{100}	Type of stratification	x_{max}	q_{max}	σ_y	σ_x	$x_{кнн}$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
61	23	6. X/1959	10 28	1000	45—65	0,12	$5,2\cdot10^{11}$	8	1,0	1,7	I	$2,60\cdot10^{4}$	$1,3\cdot10^{3}$	$1,0\cdot10^{3}$	$1,15\cdot10^{4}$	$6,7\cdot10^{4}$
62	24	9. X/1959	11 04	2000	45—65	0,12	$6,3\cdot10^{11}$	4	0,8	0,9	IV	$3,14\cdot10^{4}$	$3,4\cdot10^{3}$	$1,8\cdot10^{3}$	$1,32\cdot10^{4}$	$6,67\cdot10^{4}$
63	25	9. X/1959	17 20	1000	10—45	0,07	$3,6\cdot10^{12}$	5				$3,22\cdot10^{4}$	$1,05\cdot10^{3}$	$1,7\cdot10^{3}$	$8,4\cdot10^{3}$	$7,14\cdot10^{4}$
64	26	14. X/1959	15 37	1000	45—65	0,12	$7,7\cdot10^{11}$	8	1,1	1,1	I	$4,0\cdot10^{4}$	$1,6\cdot10^{3}$	$1,4\cdot10^{3}$	$6,8\cdot10^{3}$	$6,7\cdot10^{4}$
65	27	23. X/1959	13 05	300	80—100	0,22	$1,2\cdot10^{11}$	7	0,4	0,4	III	$2,5\cdot10^{3}$	$7,7\cdot10^{4}$	$1,2\cdot10^{2}$	$2,4\cdot10^{2}$	$9,6\cdot10^{3}$
66	28	31. V/1960	12 55	500	45—65	0,12	$5,1\cdot10^{11}$	7	0,9	0,9	III	$2,05\cdot10^{4}$	$1,7\cdot10^{3}$	$1,3\cdot10^{3}$	$8,4\cdot10^{3}$	$2,92\cdot10^{4}$
67	29	2. VI/1960	12 48	1000	10—45	0,07	$2,1\cdot10^{12}$	7	1,1	1,2	I	$1,5\cdot10^{4}$	$1,5\cdot10^{3}$	$1,7\cdot10^{3}$	$5,2\cdot10^{3}$	$10\cdot10^{4}$
68	30	3. VI/1960	12 50	500	45—65	0,12	$5,3\cdot10^{11}$	5	1,1	1,4	I	$1,40\cdot10^{4}$	$1,7\cdot10^{3}$	$1,2\cdot10^{3}$	$5,6\cdot10^{3}$	$2,1\cdot10^{4}$
69	31	7. VI/1960	12 30	1000	10—45	0,07	$1,9\cdot10^{12}$	2	1,0	1,1	II	$2,25\cdot10^{4}$	$8,4\cdot10^{3}$	$2,7\cdot10^{3}$	$6,2\cdot10^{3}$	$2,86\cdot10^{4}$
70	32	9. VI/1960	13 19	500	45—65	0,12	$1,0\cdot10^{12}$	7	1,5	1,5	I	$2,10\cdot10^{4}$	$1,2\cdot10^{4}$	$1,5\cdot10^{3}$	$7,4\cdot10^{3}$	$2,9\cdot10^{4}$
71	33	13. VI/1960	4 30	1000	10—45	0,07	$2,0\cdot10^{12}$	5				$3,70\cdot10^{4}$	$1,0\cdot10^{3}$	$1,1\cdot10^{3}$	$9,0\cdot10^{3}$	$7,1\cdot10^{4}$
72	34	15. VI/1960	10 43	1000	10—45	0,07	$2,0\cdot10^{12}$	2				$1,30\cdot10^{4}$	$5,2\cdot10^{3}$	$1,1\cdot10^{3}$	$5,2\cdot10^{3}$	$2,9\cdot10^{4}$
73	35	4. IX/1960	12 26	1000	10—45	0,07	$2,00\cdot10^{12}$	5	1,2	2,7	I	$2,75\cdot10^{4}$	$2,3\cdot10^{3}$	$1,2\cdot10^{3}$	$1,22\cdot10^{4}$	$7,14\cdot10^{4}$
74	36	5. IX/1960	12 13	1000	10—45	0,07	$2,0\cdot10^{12}$	6	1,1	1,3	I	$2,14\cdot10^{4}$	$2,7\cdot10^{3}$	$1\cdot10^{3}$	$8,2\cdot10^{3}$	$8,57\cdot10^{4}$
75	37	6. IX/1960	12 08	1000	45—65	0,12	$7,3\cdot10^{11}$	4,5	1,0	0,8	III	$3,20\cdot10^{4}$	$1,5\cdot10^{3}$	$1,8\cdot10^{3}$	$9,1\cdot10^{3}$	$3,8\cdot10^{4}$
76	38	7. IX/1960	12 09	1000	10—45	0,07	$2,0\cdot10^{12}$	7	0,9	1,6	IV	$3,0\cdot10^{4}$	$4,8\cdot10^{3}$	$1,8\cdot10^{3}$	$1,50\cdot10^{4}$	$10\cdot10^{4}$
77	39	9. IX/1960	12 15	1000	10—45	0,07	$4,3\cdot10^{12}$	5	1,2	3,0	I	$3,0\cdot10^{4}$	$4,0\cdot10^{3}$	$1,4\cdot10^{3}$	$8,1\cdot10^{3}$	$7,1\cdot10^{4}$
78	40	10. IX/1960	13 37	1000	45—65	0,12	$8,6\cdot10^{11}$	5	1,0	2,4	II	$2,94\cdot10^{4}$	$3,2\cdot10^{3}$	$1,8\cdot10^{3}$	$6,1\cdot10^{3}$	$4,17\cdot10^{4}$
79	41	11. IX/1960	13 30	1500	65—80	0,175	$8,0\cdot10^{11}$	4	1,0	1,0	I	$2,90\cdot10^{4}$	$1,2\cdot10^{3}$	$2,8\cdot10^{3}$	$7,4\cdot10^{3}$	$3,4\cdot10^{4}$
80	42	12. IX/1960	12 06	1000	65—80	0,175	$5,0\cdot10^{11}$	5				$2,42\cdot10^{4}$	$4,2\cdot10^{3}$	$1,2\cdot10^{3}$	$7,2\cdot10^{3}$	$2,86\cdot10^{4}$
81	43	12. IX/1960	15 09	1000	65—80	0,175	$1,8\cdot10^{11}$	2	1,1	1,8	I	$6,0\cdot10^{3}$	$5,5\cdot10^{3}$	$1,4\cdot10^{3}$	$7,7\cdot10^{3}$	$11,4\cdot10^{3}$
82	44	14. IX/1960	15 00	1000	65—80	0,175	$4,7\cdot10^{11}$	5	1,1	2,1	I	$2,70\cdot10^{4}$	$1,3\cdot10^{3}$	$1,5\cdot10^{3}$	$7,9\cdot10^{3}$	$2,9\cdot10^{4}$

Type II – in the lower part of the layer $\gamma > 1°/100$ m, here, the lability energy is positive, but higher than $\gamma < 1°/100$ m, inversions are lacking, and the lability energy is negative.

Type III – throughout the layer the lability energy is negative or is equal to zero, the temperature gradient is less than the dry-adiabatic or is approximately equal to it; inversions are lacking.

Four cases with inversions are conditionally referred to as the IV type of stratification. These cases are examined separately in Table 8, from which it is clear that in three from them weak high-altitude inversions were observed, but in only one was the inversion in the lower part of the boundary layer sufficiently thick. The type of stratification for each experiment is shown in Table 7.

Table 8.

No. of experiment	Height of the lower border of inversion h(m)	Thickness of the inversional layer Δh(м)	Difference of temperature at the upper and lower border of the inversional layer $\Delta t°$
10	110	290	5,5
15	2800	220	0,8
24	1000	600	1,7
38	800	130	1,1

Analysis of the results of experiments. For the period from 1956 through 1960 82 experiments were made. Their results are given in combined Table 7. Here initial data are also listed: H – height of source in meters; D – average diameter of the particles in microns; w – speed of gravitational fallout of particles in m/s; Q – quantity of particles at the source; u – speed of the average wind in the layer of propagation of particles in m/s; γ – average vertical gradient of temperature in the layer of the fallout of particles in degree/100 m; γ_{100} – vertical gradient of temperature in the lower 100 m layer of the atmosphere in degree/100 m.

Further on the basic results of treatment are given: x_{max} – distance from the projection of the release point to the maximum of

concentration found from the experiment, in meters;[1] q_{max} – maximum surface concentration (particles/m^2); σ_y – variance of dispersion of the surface particle density in a crosswind direction based on experimental data, in meters; σ_x – variance of dispersion of surface particle density in longitudinal direction based on experimental data, in meters; $x_{кин}$ – coordinate of the calculated kinematic maximum ($x_{кин}$ = uH/w), in meters.

The first experiments based on the study of propagation of particles were set in 1955. They were performed for the purpose of testing the developed method under field conditions. In the experiments particles of quartz sand, from 200 to 1000 μm in diameter were used. The particles were released at various heights from 500 to 2000 m. In Fig. 2 as an example the trace of the 250-400 μm fraction is shown, which was obtained in an experiment of 16 August 1955. The release was made from a height of 500 m during a wind of 3-4 m/s in a direction of 111°. The atmosphere was stratified stably according to altitude; the vertical temperature gradient did not exceed 0.5°/100 m. The release was made from a MI-2 helicopter, "depending" on the air above the assigned point. Numbers in the figure correspond to values of surface concentration of particles (number of particles per area, 1 m^2). In the figure are shown to isolines of concentration 10^2, 10^3 and 10^5 particles/m^2. As the figure shows, the direction of the axis of the trail (the line, passing through points of maximum concentrations) will agree well with the direction of the average wind in the layer of fallout of particles. The trace is fixed at a distance of 600 to 2100 m from the projected point of release.

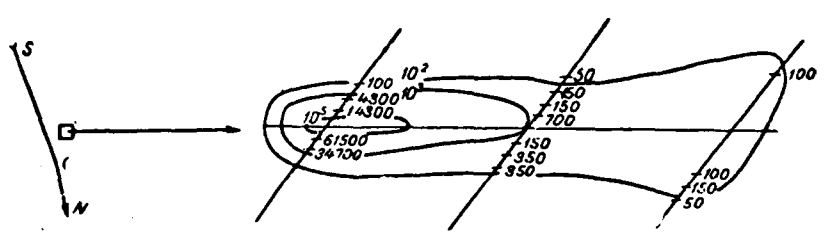

Fig. 2. Isolines of the surface particle density in the experiment of 16 August 1955.

[1]In experiments with light particles, x_{max} is the coordinate of the secondary (diffusion) maximum.

Experiments of 1955 were checked, on the basis of their being able to conclude that the testing method is adequate for the problem at hand. The obtained specific data on the value of the basic parameters of trace, which are formed in releasing the particles, 200-500 μm in diameter, permitted the running of further experiments more effectively.

In 1956 the experiments were conducted in March-May in the region of Hungry steppe of the Uzbek Soviet Socialist Republic. The particles of sand, 200-600 μm in diameter were released from heights of 500-8000 m. Results of the experiments are presented in Table 7. A description of one of the typical experiments, conducted on 21 April 1956 (experiment No. 6) is given below. The release of particles was made from a height of 1000 m.

In Table 9 the distribution of particles by size at the source is given.

Table 9.

Diameter, μm	175—225	225—275	275—325	325—375	375—425	425—475
Quantity of particles	$1,64 \cdot 10^8$	$11,7 \cdot 10^8$	$4,97 \cdot 10^8$	$6,5 \cdot 10^8$	$3,15 \cdot 10^8$	$1,09 \cdot 10^8$

The distribution of particle density on the surface of the earth is shown in Fig. 3. Length of the traces, delineated by isolines of concentration of 1000 particles/m^2 which, relative to the maximum concentration, amounts to 1/40, is equal to 3 km. After inspecting the plane table under the microscope trails of narrower fractions were separated: 225-275, 275-325, 325-375, 375-425 μm. In Figs. 4 and 5 the typical distribution of surface concentration along the x axis is shown – along the wind direction for particles of sand, 325-375 μm in diameter and in crosswind direction, at the point of maximum concentration for particles of 225-275 μm.

In 1957 for the first time experiments for the propagation of finer particles, from 10 to 300 μm in diameter from heights of 2000-5000 m were set up.

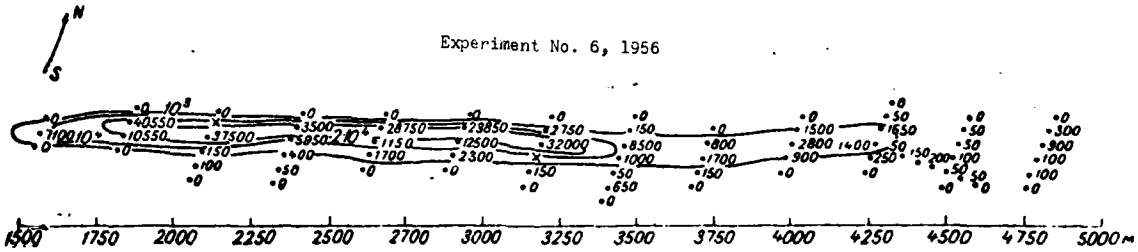

Fig. 3. Isolines of the surface particle density in the experiment from 6 to 21 October 1956.

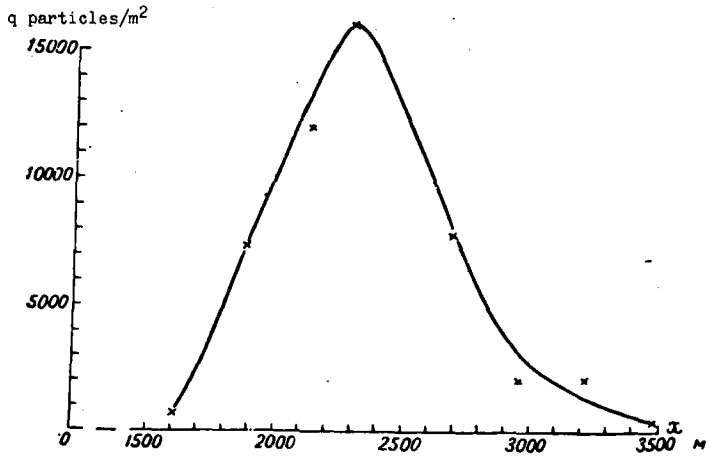

Fig. 4. Distribution of the surface particle density of sand (q), 325-375 μm in diameter along the x axis.

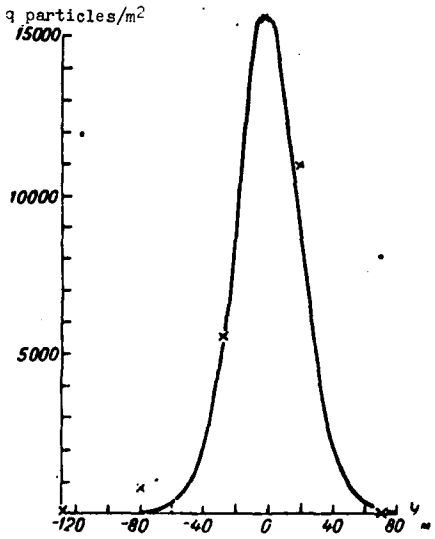

Fig. 5. Distribution of the surface concentration (q) of particles of sand, 225-275 μm in diameter in the direction of the y axis at the point of maximum concentration.

Light particles in contrast to the heavy ones, can be spread over large areas. Thus, with release from height of 1-5 km the trail of light particles covers several tens of km and a width of 1-5 km. For recovering such particles in the territory of Moscow and Kaluga Oblasts a test site with an area of nearly 6500 km^2 was marked out. Experiments were conducted during the period from June to August. Results of the experiments are presented in Table 7. Below a description of experiment No. 16, conducted on 2 July is given. The particles were released from a height of 5000 m. Distribution of the particles according to size at the source is given in Table 10.

Table 10.

Diameter, μm	100±12,5	125±12,5	150±12,5	175±12,5	200±12,5	225±12,5
Quantity of particles (%)	2,9	5,4	22,0	47,3	20,6	1,8

Isolines with concentrations of 50 particles/m^2 extend for a distance of 40 to 70 km from the point of release. The zone of maximum concentration, delineated by the 200 particles/m^2 isoline is at a distance of 63-67 km from the projection of the point of release. Maximum concentration is 250-270 particles/m^2.

In 1959, experiments with light particles were conducted in the Dnepropetrovsk region in an area, 75 km × 50 km. Particles, 10 to 100 μm, were released from heights of 300-2000 m. Results of the experiments are given in Table 7.

In 1960 experiments with light particles were also conducted in the Dnepropetrovsk region during the period from 23 May through 15 June and from 3 through 17 September. Particles 10-80 μm in diameter were dropped from heights of 500-1500 m. Below a description of experiment No. 35 is given. Particles of powder, 10-45 μm were dropped from a height of 1000 m during an average wind of 5 m/s.

In Fig. 6c and 6d the distribution of surface particle density along the x axis and in the direction of the y axis is shown. As one can see in the figure, two zones of raised concentration are

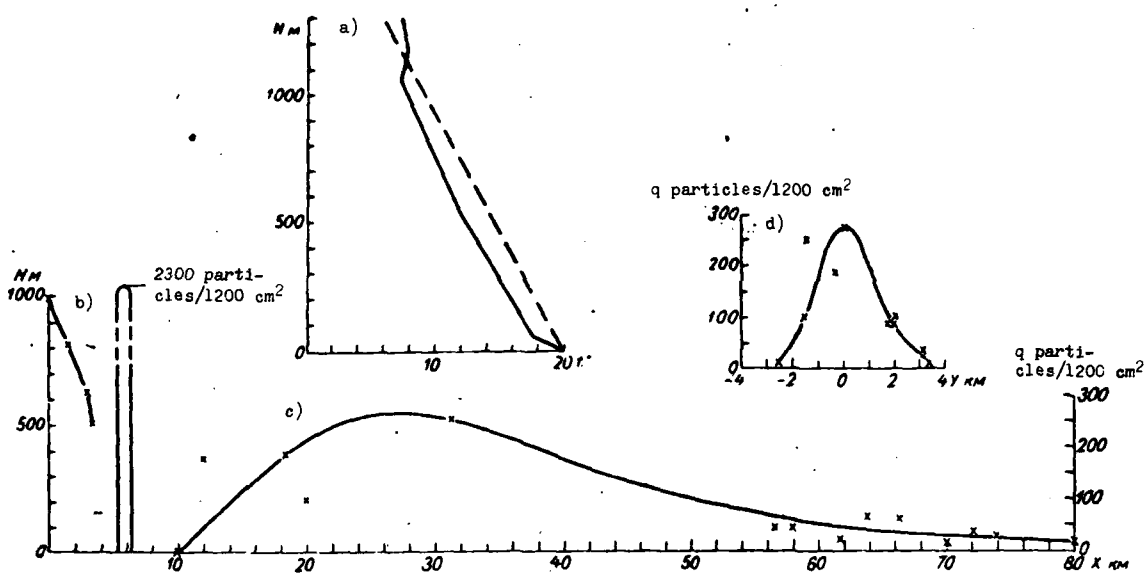

Fig. 6. Experiment No. 35, 1960. a) distribution of temperature (t°) of the air by height (H) during the period of the experiment (dotted line signifies dry-adiabatic temperature gradient), b) trajectory of the movement of the cloud of particles, c) distribution of the surface concentration (q) particles along the x axis, d) distribution of surface concentration (q) of particles in the direction of the y axis.

revealed in the trail. The first zone, with an area of nearly 4 km^2 is at a distance of 5-6 km from the projection of the release point with a maximum concentration of nearly 2300 particles in the area of the plane table (1200 cm^2). The concentration in the second zone is significantly less than in the first. The second zone is at a distance of 19-38 km (dimensions of zone are delineated by an isoline of a concentration of 200 particles/1200 cm^2). The nature of these two maxima will be mentioned below.

During the experiment visual observations from an aircraft were made behind the movement of the visible part of the cloud. The cloud was observed up to a height of 500 m. The trajectory of the movement of this cloud is shown in Fig. 6b.

In Fig. 7 the distribution of the surface particle density of the same dimensions as in experiment No. 39 is presented. The figure shows that the picture of the distribution of surface particle density is analogous to experiment No. 35.

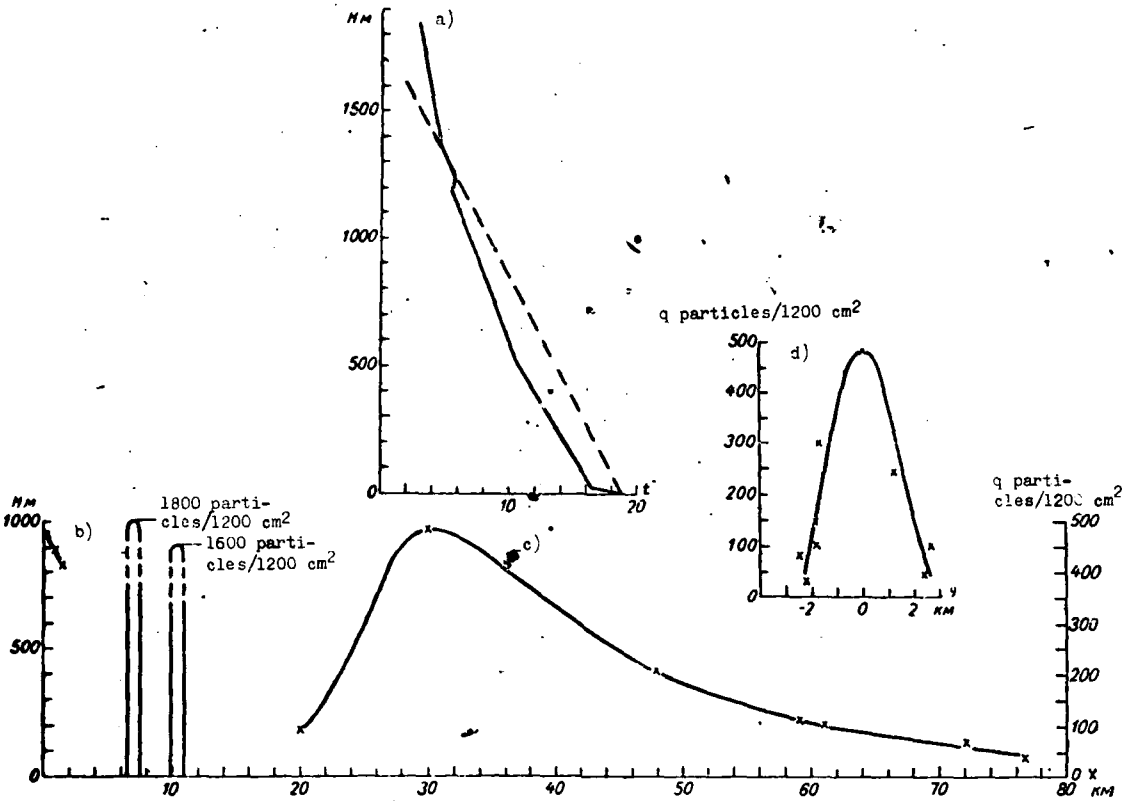

Fig. 7. [Caption illegible].

An examination of the results of the experiments shows that the picture of the distribution of surface concentration, presented in Figs. 4 and 5, is typical for particles with a speed of fallout of more, or equal to 1 m/s. The maximum of concentration of such particles is located at a distance of $x_{max} = uH/w$, where u – speed the average wind in the layer of fallout of particles, H – height of release, w – speed of the fallout of particles.

In Figs. 6 and 7 the distribution of the surface concentration of light particles, 10-80 μm in diameter ($w > 0.2$ m/s) released from a height of 1000 m is shown. As can be seen from the figures, in this case essentially another picture is observed. On earth, as a rule, two zones of increased concentration will form: the first, at a distance of 6-12 km, the second – considerably further, but at a distance of x_{max}, and in turn, smaller than $x_{кин} = uH/w$. Surface

particle density in the region of the second zone on the average is of the order of less than in the first zone. The area of the first zone is 4-9 km^2, the size of the second zone is considerably larger.

The presence of the first maximum can be explained by the features of the source of particles used, which at the time of release forms a cloud of sufficiently high concentration. In a number of cases movement of this cloud was observed, but more exactly the nucleus was an entity. It was possible to track the moving cloud from the aircraft for 10-30 minutes, depending upon its color and atmospheric composition; these observations permitted one to calculate the average speed of its movement. Comparison of results of the aircraft measurements with ground data (Figs. 6b and 7b) shows that the first maximum made up the fallout of this nucleus as an entity. Vertical velocity of the nucleus exceeds Stokes speed of individual particles by 3-5 times; it is unequal in the various experiments. More detailed knowledge on this phenomenon are presented in [7].

Based on very approximate calculations for the proportion of particles carried by the nucleus of the cloud, nearly 1/10th of the total number of particles in the cloud can be accounted for. The main mass of the cloud, having a minute density, is dispersed due to atmospheric turbulence and will form a secondary diffusion maximum of concentration on the earth, already in accordance with the fallout rates of individual particles.

A picture obtained of the trace on earth's surface as being spotty is usually somewhat incorrect. This spottiness can be determined by a number of circumstances. Aside from pure statistical error connected with the number of particles on the plane table and estimated according to the law of Poisson, the certain irregularity of the near-ground surface (microrelief; uneven vegetation, etc.) plays a role; unaccounted for features of the position of the plane table, the effect of variability of the wind. These circumstances have a greater effect in the propagation of light particles falling out over a large area than on the heavy ones.

The trail of heavy particles produces less spottiness. In spite of spottiness, in all cases the position of the maximum can be clearly determined with nearly 10% precision, and it is possible to calculate the width of the trail with approximately the same accuracy. The maximum particle density is rather poorly determined. However, even here during an evaluation of the concentration in the region of the maximum, where 200-500 particles are observed on the plane table, the statistical check is satisfactory and the concentration can be determined with an error of nearly 50% on the average.

Empirical Dependences

As mentioned above, from the qualitative side a picture of the dispersion of a pollutant impurity in the atmosphere can be presented as follows: the pollutant is transported in the direction of the wind and falls due to gravity: the action of atmospheric turbulence accentuates these movements, leading to a scattering of the pollutant. The problem is to describe this process in quantitative terms. In general terms this problem is sufficiently complex. The state of theory does not permit the consideration of all the various factors, governing dispersion, but these factors themselves in a free atmosphere cannot always be measured well.

A theoretical approach to the problem of atmospheric diffusion is found in [6, 8]. Here, we can only indicate briefly that the overall complexity of the practical use of the equation of turbulent diffusion, which is commonly used in the description of this process is, in the first place, an insufficiently known dependence entering into this equation of coefficients of turbulent dispersion in determining their parameters, inasmuch as the whole mechanism of complex interactions which characterize the physical processes of turbulent mixing in a free atmosphere, is not entirely clear. For this reason coefficients of turbulent dispersion are determined either on the basis of certain hypotheses, or on the basis of experimentation. Furthermore, the equation of turbulent dispersion itself, can be solved analytically only with defined assumptions, which are not always strictly valid for the actual process. Solutions of the

equation of turbulent dispersion of foreign bodies, ejected in a free atmosphere, are given for certain special cases, for example, in [3, 10, 11, 12].

From what was said it is clear that, as yet it was not possible to use the theory of turbulent diffusion in the interpretation of the obtained results. However, the solution of many applied problems requires simple measures, let alone approximate methods of calculation, in the propagation of various kinds of pollutants in the atmosphere. There, it would be expedient for us and very important to obtain simple empirical formulas in calculating the surface concentration of a pollutant, spread in a free atmosphere from high-altitude sources.

The attempt to estimate the coefficients of the turbulent dispersion of a pollutant in an equation, solved on the assumption that these coefficients are constant, is done in the following chapter. Here, let us stop to consider the empirical dependences and set up the problem to determine the basic parameters of the trail of falling particles in the function of the source data of the experiment – height of the release (H), rate of fallout of the particles (w), speed of the average wind (u) and the number of particles at the source (Q). The results of experiments presented in Table 7 serve as source material for given target. The experiments encompass a wide range of fall velocities of particles, from 0.07 to 3 m/s, and different heights (from 500 to 8000 m).

<u>The determination of the location of maximum particle density</u> (x_{max}). If the particles were transported only by gravity and average wind, then all of them would fall at a distance $x_{max} = uH/w$ from the projection of the point source.

In case of actual atmosphere in this picture the effect of atmospheric turbulence, resulting in the dispersion of the pollutant, applies. If the particles are coarse (their fallout speed is high), then the determining factor in their propagation is gravitational fallout, and the effect of turbulence is comparatively small. With a decrease in the size of the particles in the process of propagation,

aside from the forces of gravitation, the steadily exerting atmospheric turbulence comes into play. According to the amount of size reduction of the particles, the gravitational fallout acquires a progressively lesser value, but the role of turbulent dispersion increases. And, finally, in case of the finest particles, which can possibly be examined, almost a weightless pollutant, the effect of atmospheric turbulence completely predominates over gravitational fallout. The intensity of turbulence is determined by the field of wind and the degree of thermal stability of the atmosphere, and quite naturally such that strong winds and unstable stratification accentuate turbulent dispersion.

Thus, the value x_{max} actually depends on the speed of gravitational fallout of the particles, the speed of the wind, height of release and the thermal atmospheric composition.

In Fig. 8 is shown the dependence of a dimensionless ratio x_{max}/H on the value of the ratio u/w, which determines the relationship of speed of wind and speed of gravitational fallout of particles. Points plotted from experimental data, corresponding to values w from 2.7 to 1 m/s are represented by small crosses — in the case $w < 1$ m/s. Line 1 designates the change in value of the kinematic maximum, curve 2 is the center line, passing through the experimental points. As the figure shows, the degree of effect of atmospheric turbulence in the process of propagation of particles is characterized by the ratio u/w. Thus, when $u/w \leq 10$ the kinematic diagram of determining x_{max} is valid; when $u/w > 10$ a vertical turbulent mixing of the atmosphere begins to have a noticeable effect on the propagation of particles, the action of which shifts the maximum of surface concentration in the direction of the source ($x_{max} < x_{кин}$). At a value of $u/w > 60$, apparently, the determining factor in the propagation of particles is atmospheric turbulence. In this case the value x_{max} is around thirty-forty heights of the release for conditions close to equilibrium and to the slightly unstable stratification of the atmosphere. With an increase in the temperature instability, with other conditions being equal the influence of turbulence will be smaller in the value u/w, and the value x_{max} will decrease.

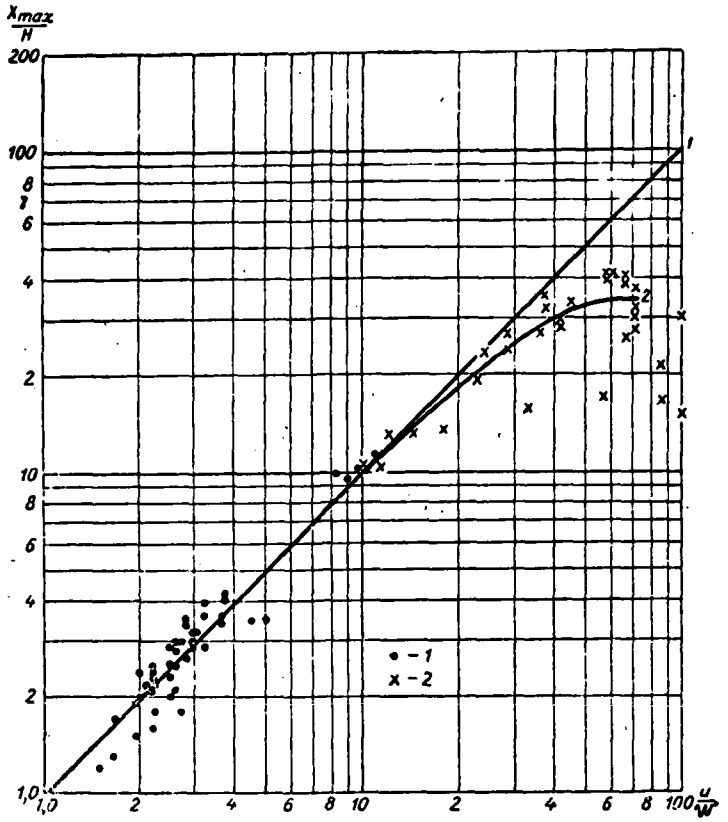

Fig. 8. Dependence of x_{max}/H on u/w. 1 – experimental data, corresponding to speeds of the fallout of particles, from 2.7 to 1 m/s and the average speeds of wind from 3 to 15 m/s, 2 – experimental data with speeds of fallout w < 1 m/s (straight line (1) signifies a change in the value of the kinematic maximum, curve (2) was plotted based on experimental data).

The dependence of $x_{max}/x_{кин}$ on u^2/w^2 is presented in Fig. 9, which shows that for range w from 0.07 to 3 m/s it can be adequately described by the empirical formula in the form

$$\frac{x_{max}}{x_{кин}} = \sqrt{\left(\mu \frac{u^2}{w^2}\right)^2 + 1} - \mu \frac{u^2}{w^2}, \qquad (1)$$

where μ – a certain dimensionless parameter, connected, apparently, with the thermal stability of the atmosphere. The values of the parameter μ, calculated for a number of experiments when H = 1000 m,

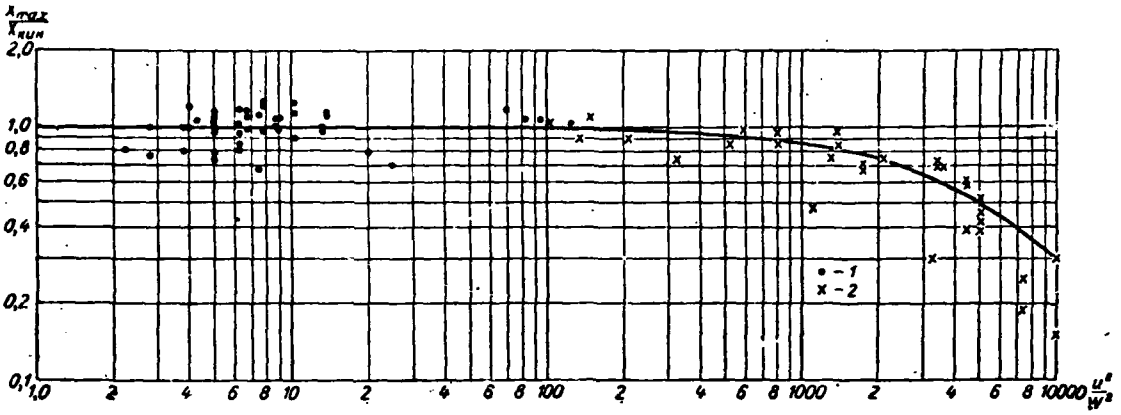

Fig. 9. Dependence of $x_{max}/x_{нин}$ on u^2/w^2. 1 – experimental data for particles with speeds of fallout of $w \geq 1$ m/s, 2 – experimental data with speeds of fallout of 1 m/s. Solid line constitutes the analytic curve according to formula (1) when value $\mu = 1.5 \cdot 10^{-4}$.

are given in Table 11. The line in Fig. 9 constitutes an analytic curve according to formula (1) when the value $\mu = 1.5 \cdot 10^{-4}$.

Table 11.

No. of trail	u	w	μ	Stratification of atmosphere
67	7	0,07	$3,3 \cdot 10^{-4}$	Unstable
74	6	0,07	$2,5 \cdot 10^{-4}$	•
73	5	0,07	$2,2 \cdot 10^{-4}$	•
77	5	0,07	$1,9 \cdot 10^{-4}$	•
63	5	0,07	$1,8 \cdot 10^{-4}$	
76	7	0,07	$1,5 \cdot 10^{-4}$	In the lower part, unstable, in the upper part, stable with inversion.
71	5	0,07	$1,5 \cdot 10^{-4}$	
61	8	0,12	$2,4 \cdot 10^{-4}$	Unstable
78	5	0,12	$1,9 \cdot 10^{-4}$	In the lower part of the layer unstable, in the upper part, stable
64	8	0,12	$1,2 \cdot 10^{-4}$	Unstable
75	4–5	0,12	$1,1 \cdot 10^{-4}$	Stable

The scattering of values μ, given in the table, is explained by distinctions of thermal atmospheric components, and also by the error of measurement of parameters x_{max}, u, H. An insufficient number of

experiments did not permit one to obtain a clear dependence of parameter μ on the stratification of the atmosphere. However, it can be stated that with increase in the degree of instability, the value μ increases.

The dispersion pattern of surface particle density, transverse and longitudinal, with respect to wind direction. As is known, the distribution of surface particle density in a crosswind direction conforms to the law of Gauss [13] and when $x = x_{max}$, has the form

$$q = q_0 e^{-\frac{y^2}{2\sigma_y^2}}.$$

Dispersion of this distribution σ_y^2 permits one to estimate the width of trace of the falling particles in the region of maximum concentration.

Inasmuch as the degree of dispersion depends on time of detecting particles in the atmosphere and on the speed of the wind, then the value of dispersion should increase with an increase in the distance from the source. The dependence of the value σ_y^2 on the distance, x_{max}, is presented in Fig. 10. Here, it is distinctly clear that this dependence, in both cases close to being linear, is different for the fine particles, ($w \leq 0.2$ m/s) and for the large ones ($w \leq 1$ m/s); on the average, the trace of large particles can be made considerably narrower. Thus, one can assume approximately

$$\sigma_y = b_y x_{max}, \tag{2}$$

where b_y – dimensionless coefficient, associated with the variability of wind direction. The average value b_y for light particles is $6.2 \cdot 10^{-2}$, and for heavy ones $1.1 \cdot 10^{-2}$; the standard deviation, accordingly is, $2.6 \cdot 10^{-2}$ and $0.3 \cdot 10^{-2}$. In Fig. 11 is shown the dependence of σ_y/H on the dimensionless parameter u/w. For the entire range of w, this dependence on the average can be represented by the formula

$$\sigma_y = a_y H \left(\frac{u}{w}\right)^n, \tag{3}$$

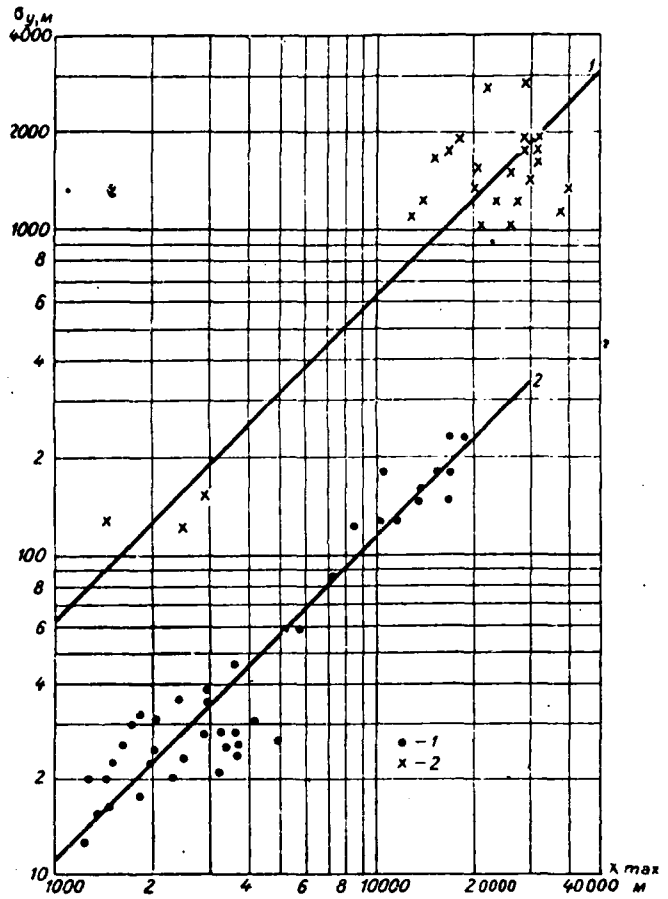

Fig. 10. Dependence of σ_y on x_{max}.
1 – experimental data, corresponding to speeds of fallout of particles $w \geq 1$ m/s,
2 – experimental data corresponding to speeds of fallout of particles $w \leq$ ≤ 0.2 m/s.

where $n = 1.3$, $a_y = 8 \cdot 10^{-3}$

In contrast to the crosswind of the distribution of particle density, which is determined only by the action of variability of wind direction, longitudinal distribution in the direction of x depends on a number of factors – on the variability of the longitudinal component of the speed of wind, on the character of vertical dispersion, on the degree of dispersion in the forming trace of particles.

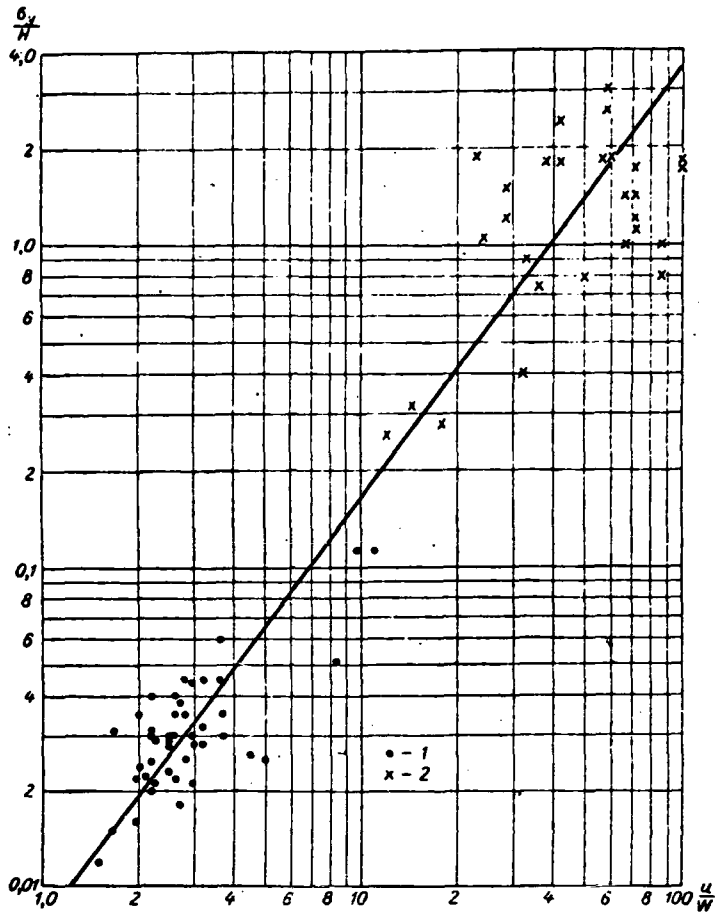

Fig. 11. Dependence of σ_y/H on u/w. 1 – experimental data for particles with speeds of fallout of $w \geq 1$ m/s, 2 – experimental data for particles with speeds of fallout of $w < 1$ m/s.

As Figures (4, 6, 7) show; the distribution of the surface concentration of heavy particles is somewhat asymmetric; it is more extended in the zone beyond the maximum than on this side of it. For light particles this asymmetry is even more substantial.

The value σ_x, which was determined by the formula $\sigma_x = \frac{l_1 + 2l_2}{3}$, was accepted as characteristic of the length of the trace where ℓ_1 – width of the distribution of surface concentration along the x axis at the level $q/q_{max} = 0.6$, ℓ_2 – the same at the level $q/q_{max} = 0.1$.

Dependence of the value σ_x/H on u/w for the entire range w is represented in Fig. 12. This dependence can, on the average, be described by the empirical formula in the form

$$\sigma_x = a_x H \left(\frac{u}{w}\right)^n, \tag{4}$$

where n = 1.15; $a_x = 1.0 \cdot 10^{-1}$.

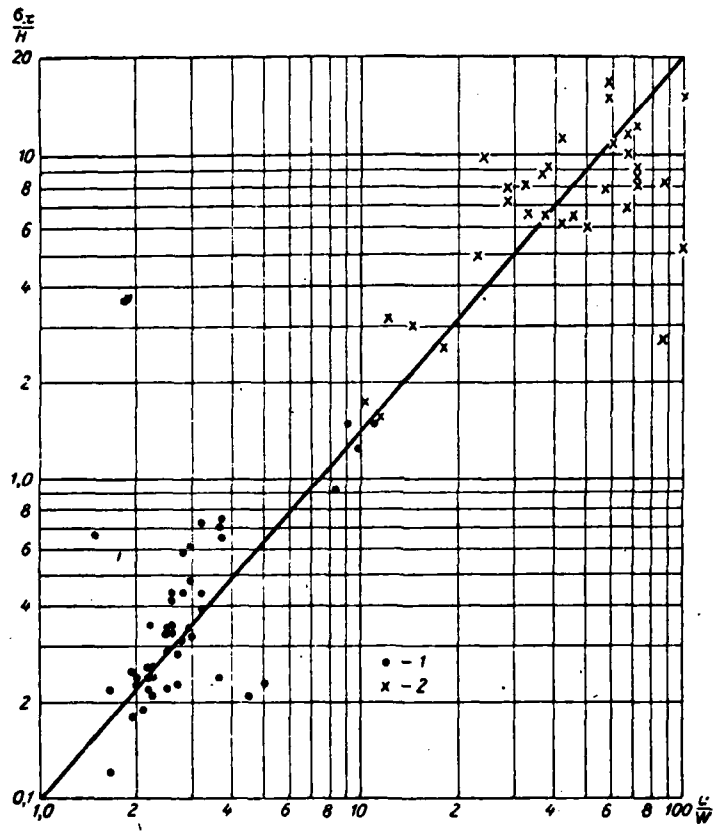

Fig. 12. Dependence of σ_x/H on u/w. 1 – experimental data for particles with speeds of fallout of $w \geq 1$ m/s, 2 – experimental data for particles with speeds of fallout of $w < 1$ m/s.

Surface particle density at a distance $x = x_{max}$. The surface concentration of the pollutant at distance x_{max} with given meteorological conditions can be determined by the quantity of particles at

the source, the speed of the wind, height of release and the speed of the fallout of particles in the atmosphere.

The dependence of a dimensionless value $\frac{1}{H}\sqrt{\frac{Q}{q_{max}}}$ on u/w for the entire range w is shown in Fig. 13. The scatter of points on the graph is sufficiently large and can be explained in the first place by the fact that under actual conditions numerous natural factors result in considerable fluctuations in the distribution of surface concentration, and the accuracy of determination entering into the calculation of the parameters is low. However, in spite of large scattering, of points in the distribution on the graph it is possible to perceive a certain pattern, which is satisfactorily described by the empirical formula in the form

$$q_{max} = A\frac{Q}{H^2}\left(\frac{w}{u}\right)^{2n} [\text{particles/m}^2], \tag{5}$$

where n = 1.4; dimensionless parameter $A = 2 \cdot 10^2$.

In conclusion of the chapter let us note that the obtained empirical dependences can be used in calculating the parameters of the trail of the released pollutant from an instantaneous point source according to assigned parameters of release (H, Q, w) and according to the average distribution of particles of wind speed (u) in the layer within range w from 0.07 m/s to 3 m/s. These dependences make it possible to calculate the maximum surface concentration and to estimate the dimensions of the contaminated zone, using expressions (1)-(5).

The obtained mean values of the empirical dimensionless parameters μ, A, b_y, useful in the case of light particles ($0.175 \geq w \geq 0.07$) at a source height of nearly 1000 m. For heavy particles, the formulas (1)-(5) are valid up to a height of 8000 m.

Evaluation of Coefficients of the Turbulent Dispersion of Particles

Basic assumptions. Aside from the obtained empirical dependences in the preceding chapter, experimental data served in the calculation

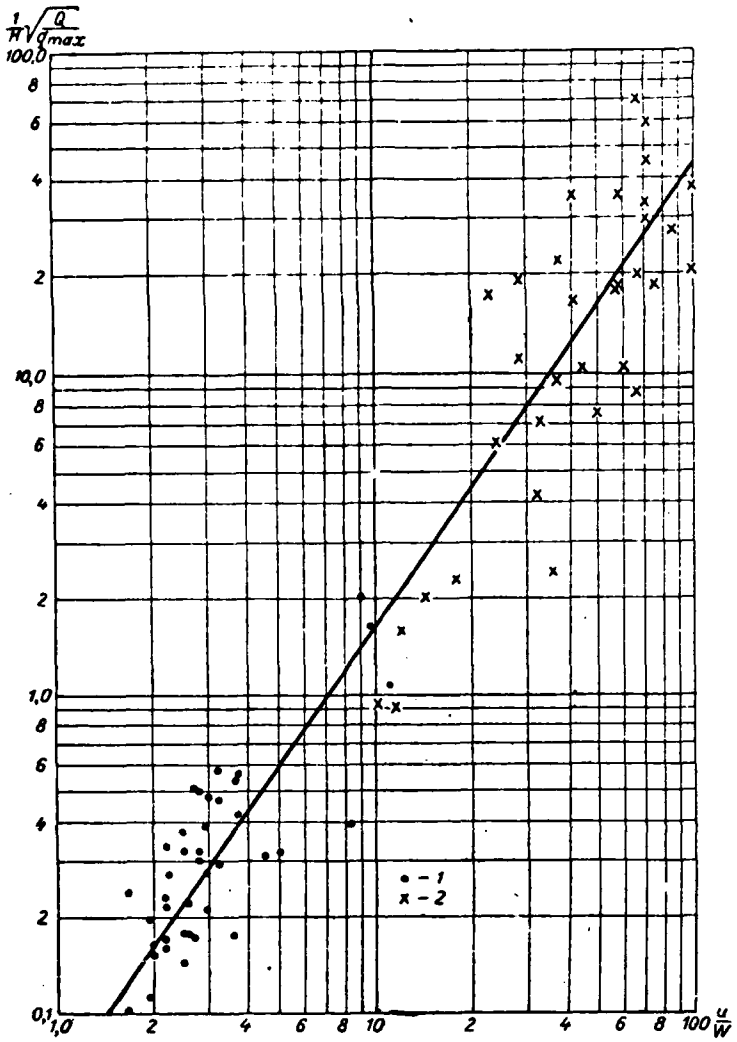

Fig. 13. Dependence of $\frac{1}{H}\sqrt{\frac{Q}{q_{max}}}$ on u/w. 1 – experimental data for particles with speeds of fallout of w ≥ 1 m/s, 2 – experimental data for particles with speeds of fallout of w < 1 m/s.

of coefficients of turbulent dispersion of the pollutant whose evaluation was used in solving the semiempirical equation of turbulent diffusion

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} - w\frac{\partial q}{\partial z} = \frac{\partial}{\partial x}K_x\frac{\partial q}{\partial x} + \frac{\partial}{\partial y}K_y\frac{\partial q}{\partial y} + \frac{\partial}{\partial z}K_z\frac{\partial q}{\partial z}, \qquad (6)$$

where q – volume of particle density, xy – eveness of the earth's surface, z – vertical coordinate, t – time, u – horizontal wind speed, w – gravitational speed of the fallout of particles, K_x, K_y, K_z – corresponding dispersion coefficients according to three directions. Inasmuch as the experimental results (distribution of the surface concentration based on a high-altitude source) represent a certain total effect of diffusion in the entire layer of propagation from the height of the source down to the surface of the earth, one can consider only the integral characteristics of diffusion in the calculation for the entire layer. Considering that the near-surface layer of the atmosphere with a strongly expressed vertical heterogeneity makes up only small portions of the layer of propagation, we will take the values K_x, K_y, K_z, independent of coordinates, and consider them parametrically dependent only on the values u, H and w.

The presence of an instantaneous source with power Q at a height H at a point x = y = 0 during the initial moment is accepted as an initial condition, when t = 0 $q = Q\delta(x)\delta(z-H)$.

The border condition which at z = 0 q = 0, expresses a condition of the complete absorption of the pollutant by the near-surface layer. The second border condition at infinity has the form

$$q = 0 \text{ when } \sqrt{x^2+y^2+z^2} \to \infty.$$

in this case the solution of equation (6) is recorded in the following form:

$$q = \frac{Q}{8\pi^{3/2} t^{3/2}\sqrt{K_x K_y K_z}} \exp\left[-\frac{w^2 t}{4K_z} - \frac{w(z-H)}{2K_z} - \right.$$
$$\left. - \frac{(x-ut)^2}{4K_x t} - \frac{y^2}{4K_y t}\right] \times \left\{\exp\left[-\frac{(z-H)^2}{4K_t t}\right]^2 - \exp\left[-\frac{(z+H)^2}{4K_z t}\right]\right\}. \quad (7)$$

Particle density on the earth's surface along the axis of the trace (y = 0) $q_{пов}$ is determined by the expression

$$q_{\text{пов}} = \int_0^\infty K_z \frac{\partial q}{\partial z}\Big|_{z=0} dt = \frac{QH}{4\pi\sqrt{K_x K_y K_z}} \times$$

$$\times \frac{\sqrt{\frac{u^2}{K_x} + \frac{w^2}{K_z}}}{\frac{x^2}{K_z} + \frac{H^2}{K_z}} \left(1 + \frac{2}{\left(\frac{xu}{K_x} + \frac{Hw}{K_z}\right)\sqrt{1+Y}}\right) \times$$

$$\times \exp\left[\frac{1}{2}\left(\frac{xu}{K_x} + \frac{Hw}{K_z}\right)\left(1 - \sqrt{1-Y}\right)\right], \qquad (8)$$

where $Y = \frac{(Hu - xw)^2}{K_z K_x \left(\frac{xu}{K_x} - \frac{wH}{K_z}\right)^2}$.

The expression (8) represents the distribution of the pollutant from an instantaneous point source along the surface of the earth (trail) and can serve in calculating the coefficients of diffusion in the comparison with experimental data.

Evaluation of the Coefficient of Vertical Diffusion K_z

The location of maximum concentration can be determined from (8) based on condition $dq/dx = 0$. In [10] it is shown that it does not depend on coefficient K_y and can be determined by values of the coefficients K_x and K_z. Likewise conditions were clarified in which the basic role is assigned to coefficient K_z. Let us repeat these results briefly. In a limiting case, when $K_x \to \infty$, the expression for the determination of the value x_{max} has the form

$$\frac{x_{max}}{x_{\text{кин}}} = \frac{1 + 2\frac{K_z}{wH}}{12\frac{K_z}{wH} + 6\frac{K_z}{wH+1}}. \qquad (9)$$

Other limiting cases give: when $K_z \to 0$ dispersion along the vertical does not occur and

$$x_{max} \to x_{\text{кин}} \to \frac{uH}{w};$$

when $K_z \to \infty$ $x_{max} \to 0$.

In the case of fulfillment of the conditions

$$\frac{K_x w^2}{K_z u^2} \leqslant 0{,}4; \quad \frac{x_{max}}{x_{кин}} \geqslant 0{,}4;$$
$$\frac{K_z}{wH} \ll 1,$$

as shown in [10], the expression (8) is simplified, assuming the form

$$q_{пов} = \frac{Q}{4\pi\sqrt{K_y K_z}} \frac{w^2}{uH} \frac{\sqrt{1+\frac{w^2 K_x}{u^2 K_z}}}{\left(\frac{x_{max}}{x_{кин}}\right)^2 + \frac{w^2 K_x}{u^2 K_z}} \times$$
$$\times \exp\left[-\frac{\frac{wH}{K_z}\left(1-\frac{x_{max}}{x_{кин}}\right)^2}{4\left(\frac{x_{max}}{x_{кин}}+\frac{w^2 K_x}{u^2 K_z}\right)}\right]. \qquad (10)$$

In this case, as calculations have shown, the value x_{max} depends basically on the coefficient of vertical dispersion K_z. The simplest expression for determining the value x_{max} based on value K_z is obtained when $K_x \to 0$; it has the form

$$\frac{x_{max}}{x_{кин}} = -\frac{4K_z}{wH} + \sqrt{\left(\frac{4K_z}{wH}\right)^2 + 1}, \qquad (11)$$

whence

$$K_z = wH \frac{1-\left(\frac{x_{max}}{x_{кин}}\right)^2}{4\frac{x_{max}}{x_{кин}}}. \qquad (12)$$

Calculations according to the formulas (11) and (9) show little difference in the results [10], thus, the value K_x within the entire possible range of changes does not have a noticeable effect on the value x_{max}.

The connection between K_z and the empirical dimensionless parameter μ can be obtained in the comparison of formulas (1) and (11)

$$K_z = \frac{\mu}{2}\frac{u^2 H}{w}. \qquad (13)$$

In Table 12 are given the values of parameter μ, defined for each trace of light particles according to the formula

$$\mu = \frac{1}{\frac{u^2}{w^2}} \cdot \frac{1-\left(\frac{x_{max}}{x_{min}}\right)^2}{2\frac{x_{max}}{x_{min}}}, \qquad (13a)$$

originating from their experimental data.

Table 12. Table of the values K_y and K_z for light spherical particles (w = 0.07-0.175 m/s; d = = 1.1 g/cm^3).

No. of trail	u	w	$\beta_y 10^2$	K_y (exper.)	K	$\mu \cdot 10^4$	K_z
			$H = 500$ м				
68	5	0,12	0,37	257		2,4	6
66	7	0,12	0,20	288		1,1	6
70	7	0,12	0,25	375		0,98	5
			$H = 1000$ м				
60	4	0,07	0,56	381		4,7	27
75	4,5	0,12	0,16	227	8	1,2	5
63	5	0,07	0,14	224		1,7	16
71	5	0,07	0,09	82		1,4	11
73	5	0,07	0,10	131	33	2,2	19
77	5	0,07	0,11	164	15	1,9	17
78	5	0,12	0,19	275	20	2,0	11
80	5	0,175	0,12	149		2,0	7
82	5	0,175	0,15	208		0,92	3
74	6	0,07	0,11	140	39	2,6	33
67	7	0,07	0,64	674	45	3,3	57
76	7	0,07	0,18	378	20	1,5	27
61	8	0,12	0,07	154	58	2,5	33
64	8	0,12	0,06	196	7	1,2	16
			$H = 1500$ м				
79	4	0,175	0,47	541		3,2	11
			$H = 2000$ м				
62	4	0,12	0,16	206		7,5	25
58	6	0,07	0,12	233		3,5	89

As shown in Table 11 above, the parameter μ depends on the atmospheric components and has the largest value in the case of the unstable stratification of the atmosphere.

In Table 12 meaning the values of K_z are also given, calculated according to the formula (12).

When H < 500 m the expression (12) can be used only in those cases where the real source is sufficiently and precisely simulated by instantaneous points. In particular, in the experiments described in this work, when H < 500 m this condition is always far from being fulfilled due to the imperfection of the dispersing aerosol device and due to such a high concentration of the substance in the cloud in the initial moment such that it is impossible not to consider this phenomenon in the calculated diagram. The case of the deposition of particles from a "crop-dusting" source, having an intrinsic speed of vertical movement, was examined in [9]. Here, for determining K_z it is necessary to know the location of extreme points of surface concentration and the speed of vertical movement of the "crop-dusting" source — a cloud of particles, moving as an entity with a loss of substance on the periphery.

In Table 12, for comparison with K_z the coefficient of turbulence K is given, calculated according to the formulas of D. L. Laykhtman [4].

$$K = \frac{2l(\lg e)^2}{\left\{\frac{d}{dz}\lg\left[(ug-u)^2+v^2\right]\right\}^2},$$

where $l = 2\omega \sin\phi$ — parameter of Coriolis, e — base, natural logarithm, u, v — vector components of the wind, u_g — speed of the geostrophic wind. The formula permits one to determine the average coefficient of turbulence in a layer from 100 m up to the level of the geostrophic wind. In certain cases the character of the change in the profile of the wind with height did not permit the calculation of coefficient K to be made. As the data in the tables show, the average values of K for the entire layer were obtained by comparison with coefficient K_z.

Evaluation of the coefficient of transverse diffusion K_y. Following from the solution of equation (6) in the case $K_x = 0$, the surface concentration in the y direction conforms to the law of Gauss, where dispersion amounts to

$$\sigma_y^2 = 2K_y \frac{x_{max}}{u}. \qquad (14)$$

Comparing this expression with the empirical formula (2) for the dispersion of surface concentration at a distance $x = x_{max}$, we will obtain the connection of the previously found empirical parameter b_y with the coefficient K_y

$$K_y = \frac{b_y^2}{2} u x_{max}. \tag{15}$$

In Tables 12 and 13 are given the values $\beta_y = \frac{\sigma_y^2}{2}$, calculated for each trace according to the formula

$$\beta_y = \frac{1}{2} \cdot \frac{\sigma_{y\,max}^2}{x_{max}^2}, \tag{16}$$

where $\sigma_{y\,max}^2$ – value of dispersion at a distance $x = x_{max}$. Mean values of β_y are determined separately for light (Table 12) and heavy particles, just as was done in examining the empirical dependences. The mean value β_y for heavy particles amounts to $0.69 \cdot 10^{-4}$, for light ones – $0.18 \cdot 10^{-2}$. In Tables 12 and 13 are given the experimental values of $K_y = \beta_y u x_{max}$ for each trail.

In Table 13 a comparison of the value K_y for heavy particles, obtained by means of calculating for mean values β_y is given. As can be seen from the tables, the value K_y for heavy particles had a value from 0.2 to 7 m^2/s, for light particles – from 80 to 700 m^2/s. As was also assumed, the value K_y turned out to depend on the speed of the fallout of particles, on the height of the source and on the speed of the wind. The biggest values of K_y were observed for light particles during a strong wind and with the source at high altitudes.

Dependence of the maximum concentration on K_x. Above it was shown that with accepted limitations the location of the maximum concentration hardly depends on the coefficient of longitudinal turbulent diffusion K_x. It is interesting to estimate the effect of K_x on the value of surface concentration at point $x = x_{max}$. Calculations according to formula (10) at various values of the parameter w^2K_x/u^2K_z show that this value depends slightly on K_x; thus, with a

Table 13. Table of values of K_y for particles with speeds of fallout w = 1.1-2.65 m/s (α = = 2.7 g/cm^3).

No. of trail	u	w	$\beta_y 10^4$	K_y experimental	K_y calculated
			$H = 500$ м		
7	4	1,1	1,55	1,05	0,50
8		1,35	1,13	0,66	0,41
9		1,55	1,02	0,57	0,36
10		1,80	1,40	0,67	0,30
1	15	1,35	0,52	4,45	5,72
2		1,55	0,68	5,20	4,98
3		1,8	0,14	1,03	4,29
			$H = 1000$ м		
11	3	1,35	1,1	0,69	0,46
12		1,55	0,68	0,39	0,40
13		1,80	1,66	0,85	0,34
14	3	1,1	0,5	0,27	0,57
15		1,35	1,22	0,59	0,46
16		1,55	0,58	0,26	0,40
17		1,8	0,66	0,26	0,34
18		2,0	0,5	0,18	0,31
19	4	1,35	0,53	0,61	0,81
20		1,55	0,38	0,38	0,71
21		1,8	0,38	0,35	0,61
22		2,0	0,72	0,58	0,55
23	4	1,1	0,78	1,12	1,0
24		1,35	0,22	0,28	0,81
25		1,55	0,68	0,82	0,71
26		1,8	0,72	0,72	0,61
27		2,0	1,06	1,02	0,55
4	5	1,35	0,26	0,53	1,28
5		1,55	0,30	0,54	1,11
6		1,80	0,28	0,48	0,96
30	6	2,0	0,38	0,73	1,24
31		2,2	0,80	1,44	1,13
32		2,4	0,47	0,82	1,04
28	10	2,0	0,25	0,88	3,45
29		2,2	0,28	0,98	3,13
			$H = 4000$ м		
33	5	1,55	0,64	3,68	4,45
34		1,8	1,44	7,63	3,84
35		2,0	0,73	3,57	3,45
36	5	1,35	0,36	3,01	5,11
37		1,55	0,64	5,09	4,45
38		1,8	0,5	3,5	3,84
39	6	2,4	0,98	4,94	4,14
40		2,65	0,7	3,02	3,75

Table 13. (Cont'd).

No. of trail	u	w	$\beta_v 10^4$	K_y experimental	K_y calculated
			$H = 7000$ м		
44	6	2,4	0,65	5,46	7,24
			$H = 8000$ м		
41	5	2,0	0,77	7,16	6,9
42		2,2	0,86	7,57	6,27
43		2,4	0,52	4,60	5,75

change in the parameter w^2K_x/u^2K_z from 0 to 0.02 it changes within limits of 5-8%; with a change of w^2K_x/u^2K_z from 0.02 to 0.20, within the limits of 15-20%. From this calculation it follows that it is impossible to determine the value K_x, bearing only on the values x_{max} and q_{max}.

Consideration of the theoretical scheme and experimental data made it possible to estimate the values of coefficients K_y, K_z and the role of coefficient K_x. A simple connection was established between the coefficient of vertical dispersion of particles K_z in the atmosphere and the location of maximum surface concentration x_{max}, and it was shown that the location of the latter and the value q_{max} hardly depend on K_x.

The comparison of the calculated and experimental data showed that the computed value of concentration at the point of maximum, in most cases, was higher than the experimentally determined ones. This can be explained, in the first place, by the imperfection of the theoretical scheme, where the transport of particles by the descending cloud is not considered. The fact that transport does exist, was repeatedly noted both during visual observations of the cloud from the aircraft, as well as on the ground. Let us note that in those cases, when the descent of the cloud was not noted, the calculated and measured values of maximum concentration were close.

Conclusions

1. Examined in this work was the dispersion of spherical

particles in a free atmosphere with speeds of fallout from 0.07 to 1 m/s, and of particles of irregular shape with speeds of fallout from 1 to 3 m/s based on materials of the experiments of 1956-1957 and 1959-1960 with releases from heights of 500-8000 m.

2. Empirical formulas were obtained, allowing one to calculate the surface particle density from a pinpoint instantaneous source, if the height of the source, the average speed of the wind in the working layer, the size and quantity of particles in the source are known:

a) with an instantaneous source of particles the trace on the earth's surface will form in the direction of the propagation of the pollutant;

b) the location of the near-ground maximum of surface particle density within the investigated speed w can be determined by the formula

$$x_{max} = x_{кин}\left[\sqrt{\left(\mu\frac{u^2}{w^2}\right)^2 + 1} - \mu\frac{u^2}{w^2}\right],$$

where $x_{кин}$ = uH/w, and μ – parameter, depending on the stratification. At the location of the maximum of heavy particles (w > 1 m/s) the atmospheric turbulence hardly has an effect, and in this case x_{max} = = $x_{кин}$. For light particles (w = 0.07-0.175 m/s) the location of the maximum of surface concentration is sufficiently stable. Thus, at a height of the source on the order of 1000 m and with an average speed of wind of 3-6 m/s, value x_{max} amounts to 30-40 heights of the source under conditions close to a neutral and slightly unstable stratification of the atmosphere;

c) the value of the maximum surface particle density for the entire range of investigated speed of fallout can be estimated according to the formula (5), where $A = 2 \cdot 10^2$, n = 1.4, and the transverse variance of distribution of the surface particle density in the direction of the y axis at a distance $x = x_{max}$ can be

determined by formula (2), where $b_y = 1.14 \cdot 10^{-2}$ for particles with $w \geq 1$ m/s and $b_y = 6.2 \cdot 10^{-2}$ for particles with $w \leq 0.2$ m/s.

3. An evaluation was made of the coefficients of the turbulent dispersion of particles K_x, K_y, K_z, entering into the semiempirical equation of turbulent diffusion, on the assumption that these coefficients are constant, but are parametrically expressed through u, H, w:

a) coefficient of vertical dispersion of particles of K_z and the coefficient of transverse dispersion of particles of K_y can be estimated by the formulas

$$K_z = \frac{1}{2} \mu \frac{u^2 H}{w}, \quad K_y = \beta_y u x_{max}.$$

These formulas are valid when $u^2/w^2 > 10^3$ for $w \geq 0.07$ m/s. Here $\beta_y = 0.5\, b_y^2$;

b) the effect of dispersion coefficient of particles K_x on the formation of surface particle density in the region of maximum is hardly substantial, and, consequently, the value K_x cannot be defined by values q_{max} and x_{max}. In the practical calculations of the trace in the region of maximum of concentration, one can disregard the coefficient K_x.

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ABSTRACT

(U) A comprehensive description and analysis are presented of experimental studies of the dispersal and fallout of solid particles (luminescent sand particles, 100-1000 Mu in diameter, and luminescent plastic particles, 30-100 Mu in diameter) dispersed at heights of 500 -8000 m in the free atmosphere and falling out at a rate of from 0.1 to 3 m/sec. The traces of the aerosol particle fallout were measured to determine the relationships between their principal characteristics (surface concentrations, positions of zones of maximum particle concentration, amount of surface concentration dispersion) and total amount of particles ejected, the wind speed, and rate of particle fallout. The information presented includes: description of experimental procedures (preparation of luminescent particles and location, description, period of operation and sizes of test sites); methods of aerological observations (pibal, aircraft); and identification and grouping of four types of atmospheric stratification. The field results are graphed, tabulated, and summarized in detail. Empirical relationships investigated related to analysis of the practical utilization of the equation for turbulent diffusion and the coefficient of turbulent mixing in the derivation of a simple empirical equation.