Estimate of the possibility of the personal sampler application to detection of viable viruses in the open atmosphere

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The usability of sampler for detection of viable viruses in the open atmosphere is estimated. Formulas are derived for recalculation of the number of detected alive virus particles in a sample to the number concentration of virus-containing aerosols. We estimated the minimum concentration of virus-containing aerosols, reliably measured by the sampler. By the example of modeled hypothetic "terroristic act" with application of virus material under urban conditions, we demonstrated the possibility of the sampler in obtaining reliable concentrations of virus-containing aerosols under real conditions.

A personal sampler for detection of viable viruses in aerosol is presented in Refs. 1 and 2. Air arriving at the sampler is bubbled through a porous membrane. During the sampling process, the virus-containing particles are accumulated in the sorbing liquid. Testing of the sampler with the use of viruses with different stabilities in environment (influenza, measles, parotitis, variolovaccine, and virus of atypical pneumonia (SARS)) has shown that up to 80% of the infectiousness of the quite labile virus of influenza is lost, while for the relatively stable virus of variolovaccine the losses are about 10%.[3] Better survival of the biological material was observed in tests of the sampler on bacteria.[1,2]

This paper presents an estimate of the usability of this sampler in the sampling of virus-containing aerosols under conditions of the open atmosphere. For viruses studied in Ref. 3, the exponential kinetics of their death in the sorbing liquid was given. On this basis, the formulas for recalculation of the number of detected alive virus particles in the sample to the number concentrations of virus-containing aerosols inhabiting air were derived.

To estimate the usability of the personal sampler, it is necessary to determine the amount of the viable viruses n, accumulated in the sorbing liquid for the sampling time T. During the time from t to $t+\Delta t$ $(0 \le t \le T)$, $\Delta n = \kappa Q C(t) \Delta t$ virus particles arrive at the sampler, where κ is the coefficient accounting for the efficiency of aspiration and trapping of virus-containing particles by the sorbing liquid $(0 \le \kappa \le 1)$; Q is the air consumption; and $C(t)$ is the number concentration of virus-containing particles in air. In the sampling process virus particles loss their biologic activity due to liquid bubbling. Therefore, simultaneously with increase of the number of virus particles associated with their arrival in the sampler, a competing process of their destruction takes place in the sorbing liquid.

Linear approximation of the logarithm of concentration of alive viruses in the sorbing liquid $C_s(t)$ for different times of bubbling of filtered air t [Ref. 3] leads to the exponential time dependence of the biologic virus activity:

$$n(t) = n(0)\exp(-t/\tau),$$

where τ is the time of the virus activity decay by a factor of $e \approx 2.72$. The correlation coefficient for experimentally obtained points relative to the straight line $\log_{10} C_s = a + bt$ for viruses, studied in the above work, ranged from -0.88 to -0.99, while τ ranged from 0.53 to 1.45 h.

After termination of the sampling because of the particle destruction, $\Delta n = \kappa Q C(t) \exp[-(T-t)]\Delta t$ viable virus particles remain in the sampler, arriving there for the time between t and $t+\Delta t$. As a result, the total number of viable virus particles in the sample at the time instant T is

$$n = \kappa Q \sum_{i=1}^{N} C(i\Delta t) \exp\left[-(N-i)\Delta t/\tau\right] \Delta t, \qquad (1)$$

where $N = T/\Delta t$ is an integer number. From Eq. (1) we obtain the formula for determination of the measured number concentration of virus-containing aerosols $C'_{\text{mes}} = n/(QT)$, expressed via the measured concentration $C(t)$:

$$C'_{\text{mes}} = \int_0^T C(t) \frac{\kappa}{T} \exp\left[-(T-t)/\tau\right] \mathrm{d}t. \qquad (2)$$

In a general case, the medium, where atmospheric admixtures propagate, is turbulent. Therefore, C and, hence, C'_{mes} are random quantities. Applying to Eq. (2) the procedure of averaging over statistical ensemble, we obtain

$$\langle C'_{\text{mes}} \rangle = \int_0^T \langle C(t) \rangle \frac{\kappa}{T} \exp\left[-(T-t)/\tau\right] \mathrm{d}t,$$

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where angular brackets mean averaging over the statistical ensemble. If the samples are collected under stationary conditions of propagation of virus-containing aerosols in the atmosphere, then $\langle C(t)\rangle = C_0 = \text{const}$ and

$$\langle C'_{\text{mes}}\rangle = \kappa\frac{\tau}{T}\left[1-\exp(-T/\tau)\right]C_0. \qquad (3)$$

It follows from Eq. (3) that, in the general case, the mathematical expectation of estimate (2) is biased because the quantities $\langle C'_{\text{mes}}\rangle$ and C_0 do not coincide. The unbiased estimate C_{mes} can be obtained by introducing an additional multiplier to Eq. (2):

$$C_{\text{mes}} = \frac{T}{\kappa\tau\left[1-\exp(-T/\tau)\right]}\int_0^T C(t)\frac{\kappa}{T}\exp\left[-(T-t)/\tau\right]\mathrm{d}t. \qquad (4)$$

Indeed, applying to Eq. (4) the averaging procedure over statistical ensemble yields $\langle C_{\text{mes}}\rangle = C_0$.

The random stationary processes possess the ergodicity property. Therefore, the averaging procedure over statistical ensemble for them is equivalent to the time averaging procedure (see, e.g., Ref. 4). In essence, formula (4) represents a linear estimate of the value of the weighted realization, average-integrated on the interval $(0, T)$:

$$C_{\text{mes}} = \int_0^T C(t)h(t)\,\mathrm{d}t, \qquad (5)$$

where

$$h(t) = \frac{1}{\tau}\frac{\exp\left[-(T-t)/\tau\right]}{\left[1-\exp(-T/\tau)\right]}$$

is the deterministic weighting function, normalized to the unity on the interval $(0, T)$.

Thus, if in processing data, obtained with the use of the personal sampler,[1,2] the exponential kinetics of virus death in the sorbing liquid is assumed, then the unbiased estimate of the number concentration of the virus-containing aerosols C_{mes} can be obtained by multiplying $C'_{\text{mes}} = n/(QT)$ by the factor $\mu(T/\tau)$:

$$C_{\text{mes}} = \mu(T/\tau)\frac{n}{QT};\quad \mu(T/\tau) = \frac{T/\tau}{\kappa\left[1-\exp(-T/\tau)\right]}. \qquad (6)$$

The dependence of the correction factor μ on the normalized sampling time T/τ is presented in Fig. 1*a*. It is seen that, the longer is the sampling time T, the larger is the μ magnitude.

According to Ref. 4, the formula for the variance of estimate of the concentration [Eq. (5)] σ^2_{mes} in the stationary case has the form

$$\sigma^2_{\text{mes}} = 2\int_0^T B(\xi)\int_0^{T-\xi} h(t)h(t+\xi)\,\mathrm{d}t\,\mathrm{d}\xi, \qquad (7)$$

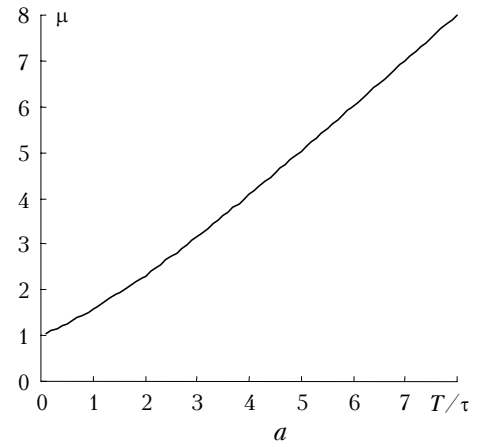
where $B(\xi)$ is the correlation function of variations of the virus-containing aerosols concentration. In Ref. 5, the theory of Markov processes is used to substantiate the following form of the stationary correlation function of variations of the atmospheric admixture concentration:

$$B(\xi) = \sigma^2\exp\left[-\frac{|\xi|}{\tau^{(E)}}\right], \qquad (8)$$

where σ^2 is the variance of the atmospheric admixture concentration; $\tau^{(E)}$ is the Eulerian timescale of turbulent wind velocity variations. The use of Eq. (8) in Eq. (7) leads to the formula

$$\sigma^2_{\text{mes}} = \frac{2\sigma^2}{\tau^2\left[1-\exp(-T/\tau)\right]^2}\times$$

$$\times\int_0^T\exp\left[-|\xi|/\tau^{(E)}+\xi/\tau\right]\int_0^{T-\xi}\exp\left[-2(T-t)/\tau\right]\mathrm{d}t\,\mathrm{d}\xi.$$



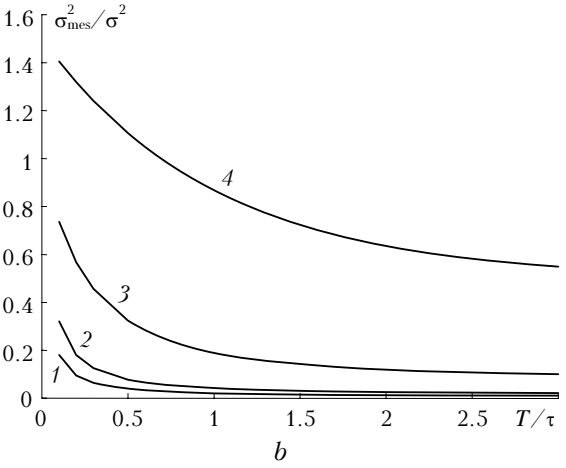


Fig. 1. Dependences of correction factor μ on T/τ (*a*) and $\sigma^2_{\text{mes}}/\sigma^2$ on T/τ (*b*). Curves *1–4* are plotted at $\tau/\tau^{(E)} = 100$, 50, 10, and 2.

The integration yields

$$\frac{\sigma^2_{\text{mes}}(T)}{\sigma^2} = \frac{1-\exp\left[-(1+\tau/\tau^{(E)})\,(T/\tau)\right]}{\left[1+\tau/\tau^{(E)}\right]\left[1-\exp(-T/\tau)\right]^2} +$$

$$+\frac{\exp\left[-(2T)/\tau\right]\left\{1-\exp\left[(1-\tau/\tau^{(E)})\,(T/\tau)\right]\right\}}{\left[1-\tau/\tau^{(E)}\right]\left[1-\exp(-T/\tau)\right]^2}. \qquad (9)$$

The parenthesized argument in $\sigma^2_{\text{mes}}(T)$ implies that the sampling lasts during the time interval T.

Figure 1*b* presents the dependence of σ^2_{mes}/σ^2 on T/τ. It follows from these plots that σ^2_{mes}/σ^2 grows with decrease of $\tau/\tau^{(E)}$ and tends to zero at $T/\tau \to +\infty$. It is seen that for the variance of the measurements less than a certain threshold value, the measurements should be made for a sufficiently long time period. For instance, if for $\tau/\tau^{(E)} = 50$ we set $\sigma^2_{mes}/\sigma^2 < 0.05$, then $T/\tau > 0.9$. The values of timescale $\tau^{(E)}$ in the near-ground atmospheric layer are about tens to hundreds of seconds (see Ref. 6). Therefore, in the considered case, the curves *1* and *2* in Fig. 1*b* best correspond to the real sampling conditions.

With some restrictions, the derived formulas can also be used in the case of sampler operation under conditions of the concentration fields of virus-containing aerosols, non-stationary in time. For the sampling times T much larger than the Eulerian timescale $\tau^{(E)}$, the ergodicity condition is fulfilled approximately,[4] and formula (5) remains unchanged. The expression for the variance of unbiased estimate for non-stationary case can be obtained from formula (7) by assuming in it the quasi-stationary form of the correlation function of concentration pulsations[7]:

$$B(t,\xi) = \sigma^2(t)\exp\left[-\frac{|\xi|}{\tau^{(E)}}\right].$$

The quasi-stationarity is manifested in the fact that in addition to quite slowly, on the average, varying $C(t)$ on the interval $(0, T)$, rapid pulsations with frequencies about $1/\tau^{(E)}$ are superimposed on the concentration variation process. In this case

$$\sigma^2_{mes}(T) = \frac{2}{\tau^2\left[1-\exp(-T/\tau)\right]^2} \times$$

$$\times \int_0^T \exp\left[-|\xi|/\tau^{(E)} + \xi/\tau\right] \int_0^{T-\xi} \sigma^2(t)\exp\left[-2(T-t)/\tau\right] dt\, d\xi.$$

The performance of the personal sampler implies its motion in space along some route during the sampling process. Divide the sampling period T into K non-overlapping time intervals. Now, suppose that for the kth interval $(k = \overline{1, K})$ the time varies from T_k to $T_k + \Delta T_k$. If the aerosol concentrations on the time intervals T_k are statistically pair-wise independent, then, provided that $T = \sum_k \Delta T_k$, the unbiased estimate of the concentration can be obtained from formula (6). Moreover, this estimate reflects the average integrated concentration on rout. The variance of this unbiased estimate $\sigma^2_{mes\,K}$ is determined as the sum of the variances for all time intervals T_k:

$$\sigma^2_{mes\,K} = \sum_k \sigma^2_{mes}(T - T_k).$$

Estimate the minimum virus particle number concentration detectable by this sampler. The errors of determination of virus concentration in the samples are usually assessed by 95% confidence interval, within which the dispersion of the decimal logarithm of the measurements of the number concentration falls, expressed in particles/ml [Ref. 8]. In our case, the 95% confidence interval is no more than 1/2 of the decimal logarithm or $10^{0.5} \approx 3$ particles/ml, in units of virus particle concentration in liquid. This value corresponds to the concentration of virus-containing aerosols in air of about $2.5 \cdot 10^4/T$, where T is taken in minutes and the concentration in particles/m^3. Values of the virus number concentration in the sample, that are equal to or less than the errors indicated above, cannot be considered as reliable. Expression, estimating the minimal virus-containing aerosol number concentration C_{min}, detectable by this sampler, is followed from Eq. (6):

$$C_{min}(\text{particles}/m^3) \approx \frac{2.5 \cdot 10^4}{T(\text{min})} \frac{T/\tau}{\kappa\left[1-\exp(-T/\tau)\right]}. \quad (10)$$

The dependence of C_{min} on T/τ, within a constant factor, corresponds to the behavior of the curve presented in Fig. 1.

To determine the fields of the mathematical expectation of virus-containing aerosol concentration, we used the semiempirical equation of turbulent diffusion.[9] The z-axis was directed vertically upward, while the x- and y- axes in the eastward and westward directions, respectively, in the horizontal plane. Note that the derivation of the semiempirical equation also suggests the fulfillment of the condition that the time of propagation of the atmospheric admixture T is much more than the Eulerian timescale $\tau^{(E)}$. Thus, the formulas for determination of the unbiased estimates of virus-containing aerosol concentration and the used method of simulation of concentration fields are mutually agreed.

To specify the values in the semiempirical equation of wind velocity components, we used the numerical-analytical model.[10] In this model, the presence of buildings, constructions, and other orographic elements on the site is taken into account by setting the corresponding surface roughness parameters. The components of the tensor of turbulent diffusion coefficients were specified in accordance with experimentally justified (in the field) hypothesis on their proportionality to the corresponding components of the tensor of viscous Reynolds stresses[8] which, in turn, were determined using algebraic model for turbulent flows and stresses described in Ref. 11. The semiempirical equation was solved by the finite-difference methods using the split procedure with respect to physical processes and spatial variables (see, e.g., Refs. 12 and 13).

In the calculations, we have considered a hypothetical episode associated with mass meeting held at the central square of Novosibirsk (Fig. 2*a*).

The meeting was held from 15.00 to 16.00 LT under meteorological conditions typical for mid-July. The territory with crowd is marked by dashed line in Fig. 2*a*. The calculations assumed the south-westerly wind with speed of 2 m/s at the height $z = 5$ m above the underlying surface at the western boundary of the considered region (point "W" in Fig. 2*a*).

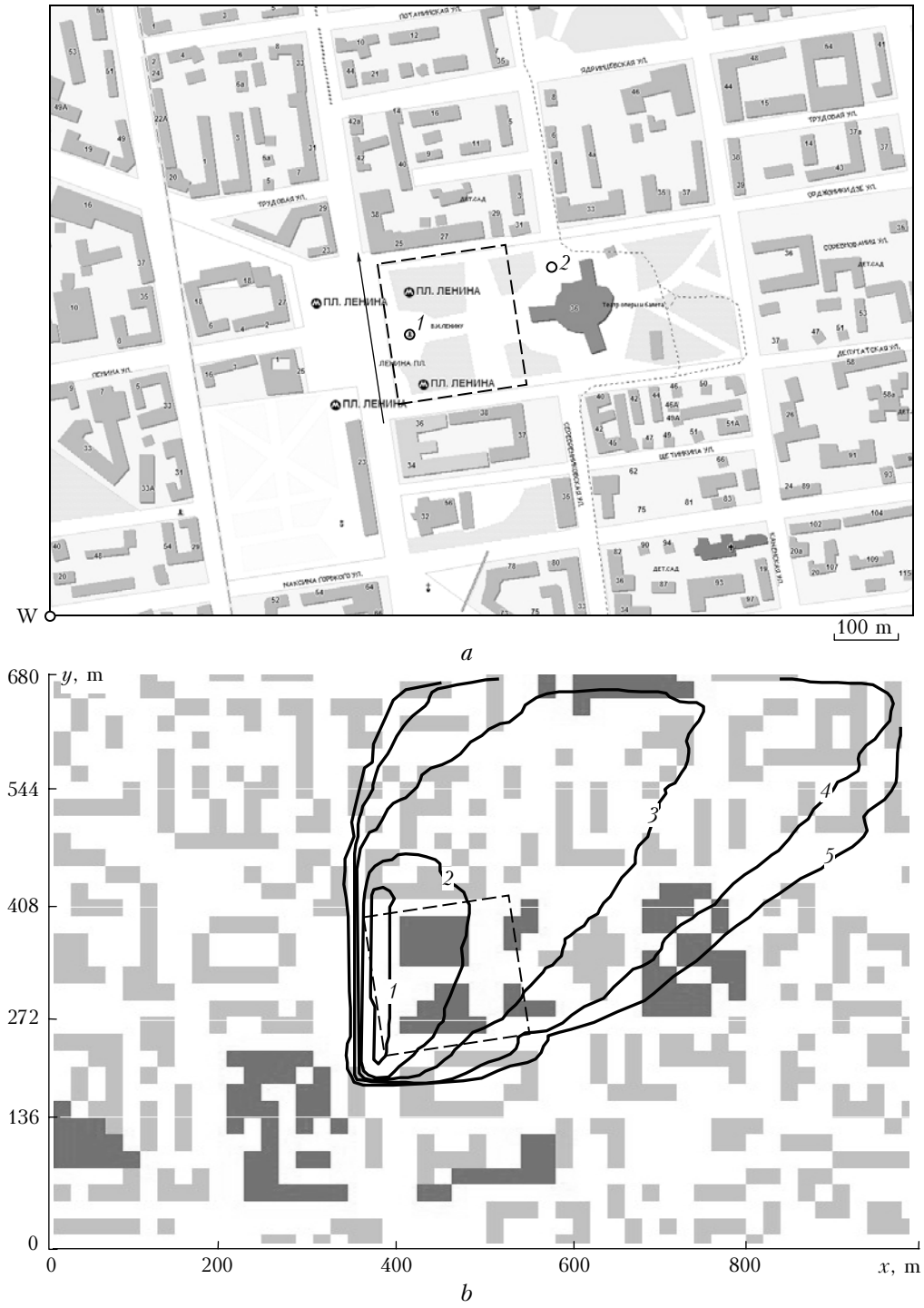


Fig. 2. Plan view of the center of Novosibirsk (database "All Russian Cities 2005 GWCY-03/05", IGNIT Company Ltd).

According to legend, during the meeting the "terrorists" undertook masked application of chemicals with pathogenic organisms of highly dangerous aerosol-form virus infection, which has led to disease of population. The automobile with aerosol source (indicated by arrow) moved along the central street of the city at a speed of 18 km/h. The length of aerosol spraying track was 250 m. A total of 250 g of chemicals with virus concentration of $5 \cdot 10^{10}$ particles/g were released to the atmosphere along the spraying track at a height of 2 m above the underlying surface. The spray episode started at 15.00 LT and lasted for 40 s, much shorter than the meeting duration. Therefore, the term describing the source was specified as the "instantaneous" linear source, actuated at 15.00 LT. It was assumed that the virus did not lost its activity during its travel. The aerodynamic particle diameter was 5 μm. The calculations were made on a finite-

difference domain of 51×35×50 nodes in size, with a step of 20 m in the horizontal direction and 1.5 m in the vertical one, respectively.

Figure 3 presents the dependence of the virus-containing aerosol number concentration $<C>$ on the propagation time; it is calculated for the height $z = 1.5$ m above the underlying surface for points numbered *1* and *2* in Fig. 2*a*. It is seen that the aerosol cloud traverses the region, marked by dashed line, in time less than 5 min.

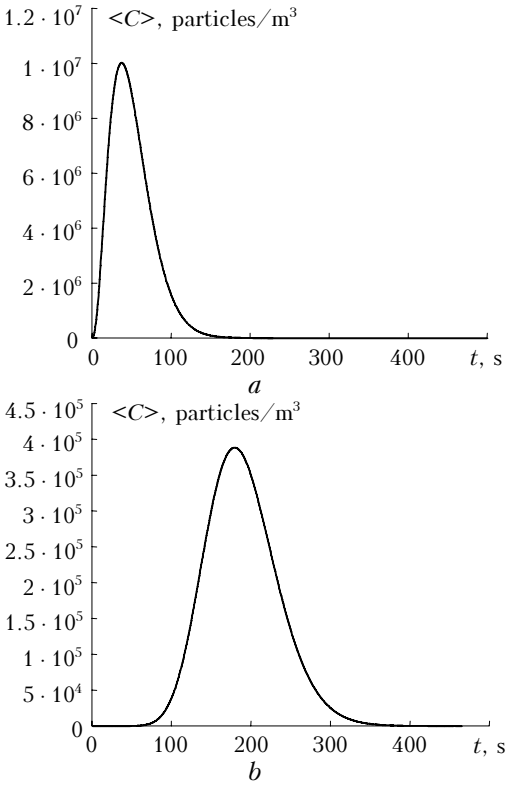


Fig. 3. Dependence of mathematical expectation of virus-containing aerosol number concentration $<C>$, calculated for points *1* and *2* (see Fig. 2*a*) on the time t passed since the chemicals were spraying: for the points *1* (*a*); and *2* (*b*).

The sampling parameters were as follows: $\kappa = 1$; $\tau = 3600$ s; the sampling height $z = 1.5$ m; the sampler, located at some fixed point in the region, marked by dashed line (Fig. 2), was switched on at the onset of the spraying episode and operated during $T = 10$ min. Under the given conditions, the correction factor μ in Eq. (6) is equal to 1.09.

Figure 2*b* presents the scheme of the calculational region in the form, in which it was approximated on the calculational domain. Shown in light-gray are buildings, and in dark-gray the vegetation cover: trees, lawns, and shrubbery. Also, Figure 2*b* presents the contour lines of the mathematical expectation of virus-containing aerosol concentration, obtained by applying to formula (5) the procedure of averaging over the statistical ensemble:

$$<C_{\text{mes}}> = \frac{1}{\tau\left[1-\exp\left(-T/t\right)\right]}\int_0^T <C(t)> \exp\left(-\frac{T-t}{\tau}\right) \mathrm{d}t.$$

Levels of solid contour lines *1*–*5* in Fig. 2*b* correspond to the measured number concentrations $<C_{\text{mes}}(T_1)> = 2.5 \cdot 10^7$, $5 \cdot 10^6$, $5 \cdot 10^5$, $5 \cdot 10^4$, and $5 \cdot 10^3$ particles/m^3. In the considered case, $C_{\min} \approx 2.7 \cdot 10^4$ particles/m^3. The fourth contour line completely covers the territory of the meeting. Thus, in the considered case, all the data, obtained by the samplers inside the region, marked by the dashed line, can be considered reliable.

To estimate the order of magnitude of σ^2_{mes} we use formula (9). Determine the timescale $\tau^{(E)}$ from the empirical formula $\tau^{(E)} \approx (45 \pm 8)z/U$, where z should be taken in meters, and U is the modulus of the wind velocity at the height z in m/s [Ref. 8]. In the considered case $\tau^{(E)} \approx 70$ s. Therefore, the curve *3* in Fig. 2*b* corresponds to the dependence of $\sigma^2_{\text{mes}}/\sigma^2$ on the normalized sampling time T/τ. It is seen that, for the given sampling conditions, errors in C_{mes} estimates are $\sigma^2_{\text{mes}}/\sigma^2 \approx 0.7$, which is quite a large value.

Thus, if for the personal sampler[1,2] the exponential kinetics of virus particle death in the sampling process is assumed, then to obtain unbiased estimates of virus-containing aerosol number concentration, the calculations of $C'_{\text{mes}} = n/(QT)$, besides inclusion of the efficiency of particle trapping by the sampler κ, should also incorporate the correction factor μ [see formula (6)], whose physical nature is associated with exponential kinetics of destruction of virus particles in suspension during air bubbling through a porous membrane.

The correction factor depends on the sampling time T and the characteristic virus activity decay time τ. The correction factor increases with growing T/τ. After introduction of the corrections, we obtain the average-integrated number concentration on the sampling time interval from t to $t + T$. The variance of the unbiased estimate of virus-containing aerosol concentration C_{mes} is determined by formula (9). The variance of the unbiased estimate of the concentration σ^2_{mes} decreases with the increase of T and grows with the decrease of $\tau/\tau^{(E)}$. Values of the virus-containing aerosol number concentration, lower than the threshold defined by formula (10), cannot be considered confident.

The approaches outlined above can be applied to any other kinetics of the virus death in the sampler. Obviously, in this case, formulas (6), (9), and (10) will change their form.

The performed model calculations show that the application of the personal sampler under conditions of the actual atmosphere may ensure detection of virus-containing aerosols and provide reliable estimates of their number concentration, averaged on the sampling interval.

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