The study of the particulate matter’s adhesion regularities on the vertical buildings’ and structures’ surfaces

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Abstract. Due to the increased level of background concentrations of pollutants in the urban air environment caused by the environmental factors and increasing annually to a greater extent due to the anthropogenic processes such as industry, transport, housing and communal services, the atmospheric air of the urban environment needs protection. One of the main environmental factors that negatively affects air, and, as a result, the environmental objects, are the solid particles (dust). The article discusses the laws of the adhesion process of the particulate matter contained in air to the buildings and structures’ vertical surfaces, which are made of various building materials. Based on the experimental studies, the regression dependencies were obtained for calculating the values of sticking and removal of solid particles on various vertical surfaces from the random determining factors. The formulas for determining the annual, seasonal, and other dust pollution of vertical surfaces made of construction and finishing materials most typical for the urban environment, are obtained; on the basis of which the methods and a program for calculating current pollution, as well as forecasting dust pollution of the buildings and structures’ vertical surfaces, located in an urban environment, have been developed. Thus, the conducted studies contribute to the solution of a number of problems related to improving the environmental safety of construction and urban economy.

Introduction
Currently, considerable attention is paid to the environmental safety problem of construction and urban economy, which is formed at all stages of the buildings and structures’ life cycle, including during their operation. At this stage, the influence of environmental factors on objects, especially atmospheric pollution, which leads to damage and subsequent destruction of objects and, as a consequence, to a decrease in the environmental quality and an increase in its negative impact on humans, is especially significant.

One of the main environmental factors that negatively affects the objects of the urban environment are the solid particles (dust) contained in the air. They are the particles of natural and anthropogenic origin that are in the air under the air currents’ influence and settle on various surfaces together with precipitation or under the influence of gravity [1-3]. An increase in the maximum permissible concentration of dust, including fine particles PM10 and PM2.5, which diameter does not exceed 10 μm and 2.5 μm, respectively, in the cities atmospheric air threatens the cardiovascular and respiratory systems’ diseases occurrence for the residents [4]. If the amount of the work devoted to the effect of polluted air on human health is a significant amount, then insufficient attention is paid to the pollution...
of urban vertical surfaces made of various building and finishing materials. However, to improve the ecological safety of the urban environment, the study of these processes is extremely necessary, therefore, the topic of the study is relevant.

**Materials and Methods**

One of the main processes that takes place in atmospheric air and negatively affects the appearance of buildings and structures is dust adhesion - the interaction of particles with a solid surface, due to forces that depend both on the properties of the contacting bodies and on the medium properties [5]. Atmospheric aerosol of urban environment (AAUE), which settles on the vertical surfaces of building objects, is an integral part of the adhesive process and represents both particles of natural and anthropogenic origin, and a whole range of polluting agents, including soot, bacteria, viruses and other contaminants. In the absence of adhesion, dust during its deposition on various surfaces would continuously return to the atmosphere due to air currents, and its concentration in atmospheric air would reach a huge value [5]. As a result of dust buildup on the surfaces of buildings and structures, dark deposits form over time, which are the solid particles’ accumulation, which leads to undesirable aesthetic effects, and also jeopardizes the materials’ integrity. Thus, the choice of the research direction is determined by the need to study the pollution patterns of the urban vertical surfaces made of various building and finishing materials with solid particles (dust) contained in the atmosphere, because this is the basis for maintaining the external appearance of construction projects that demonstrate the architectural and design features of various historical periods of the country’s development.

In order to study the buildings and structures’ pollution patterns, we conducted the experimental studies of the solid particles’ adherence process on vertical surfaces, which are made of various building materials. Particle contamination of buildings consists of such adhesion process components as “particle sticking” and “particle removal” - processes that occur in certain directions of the air flow to a vertical surface, contributing to the dust particles’ adhesion to the surface, or their removal (deflation) from it [6]. The authors developed a plant for dusting the vertical surfaces made of various construction and finishing materials, the most characteristic of the urban environment (Figure 1) [7]. As investigated vertical surfaces, such samples as glass, steel, plastered, painted surfaces and other building and finishing materials were studied. Thus, when conducting the experimental studies on the solid particles’ adherence to the surface, the mass fraction of adhering city dust particles to the vertical surface was selected as a response function $\gamma_{Fmass}$, and in experimental studies on the solid particles’ removal from the surfaces - the mass fraction of the urban dust particles that come off a vertical surface under the influence of wind per unit time: $\gamma_{Amass}$. The plan of the full factorial experiment, which is a planning matrix corresponding to the central composite rotatable plan, has been implemented. The experimental data were processed using the STATISTICA software package [6].
Experimental studies of the AAUE adhesion on vertical surfaces. Regression dependences were obtained for AAUE sticking to various vertical surfaces from four environmental and climatic factors: dust concentration in the air stream $C$, mg/m$^3$; maximum particle size $d$, μm; air flow rate $V$, m/s; cosine of the air flow angle to a vertical surface, $\phi$ [6].

1. The test sample of a vertical surface is a glass surface. Under the glass surface in the work is meant a surface treated in the highest class of cleanliness, i.e. the smooth vertical surface [8]:

$$\gamma_{F_{\text{glass}}}=0.00235 - 0.00589C - 0.0002988d + 0.00087V + 0.0055\phi + 0.003992C^2 + 0.00000998d^2$$ (1)

2. Test specimens of a vertical surface – plastered and painted surfaces. A plastered surface in the work is understood to mean a vertical surface finished with mineral plaster and corresponding to a surface cleanliness class of 10 or lower. Under the painted surface, a vertical surface painted with perchlorovinyl facade paint for outdoor works and corresponding to a surface cleanliness class of 10 or lower is accepted in the work [8]:

$$\gamma_{F_{\text{plaster}}} = -0.00472 + 0.002432C + 0.0001104d + 0.001114V + 0.006667\phi$$ (2)

3. The test specimen vertical surface – metal (steel) surface. Under a metal (steel) surface, a vertical surface is accepted in the work, processed in accordance with the 10$^{th}$ class of the surface cleanliness or lower [8]:

$$\gamma_{F_{\text{metal}}} = -0.002737 + 0.00195C - 0.00024d + 0.0005V - 0.000319\phi + 0.000009d^2 + 0.00078V \cdot \phi + 0.0001589d \cdot \phi$$ (3)
Experimental studies of the urban dust particles’ removal from the vertical surfaces. In our opinion, in addition to the previously studied climatic factors (speed and direction of the air flow), the size of the dust layer that had previously adhered to the surface is also important. Regression dependences were obtained for the removal of dust particles from various vertical surfaces from three random factors: the density of dust sticking to vertical surfaces $G$, mg/m$^2$; air flow rate $V$, m/s; cosine of the air flow angle to a vertical surface, $\phi$. The regression coefficients’ negative values are conventionally used to illustrate the process of removal (blowing) of particles from the surface [6].

1. Test samples of a vertical surface – plastered and painted surfaces:

$$\gamma A_{\text{max, p.}} = -0.99527 - 0.00007G + 0.00108V - 0.00378\phi + 0.00033G \cdot \phi - 0.001086V \cdot \phi$$  \hspace{1cm} (4)

2. Test specimen vertical surface – glass surface:

$$\gamma A_{\text{max, glass}} = -0.99499 + 0.00012G + 0.000005V - 0.0074\phi + 0.000005G^2 + 0.00376\phi^2$$  \hspace{1cm} (5)

3. Test specimen vertical surface – metal (steel) surface:

$$\gamma A_{\text{max, metal}} = -0.99837 + 0.00013G + 0.000005G^2$$  \hspace{1cm} (6)

The mathematical models’ adequacy was determined by the Fisher criterion, the significance of the calculated regression coefficients for the sticking and removal the urban dust particles on the vertical surfaces from the random factors was determined by the Student criterion.

Results and discussions

Based on the experimental studies’ results, it was found that in both experiments, the speed and direction of the air flow to a vertical surface are the most significant. However, during the dust particles’ removal process from the vertical surfaces, in addition to these factors, the sticking density (the value of the previously adhering dust layer on vertical surfaces) is of particular importance – $G$, mg/m$^2$).

It is experimentally proved that vertical surfaces dusting is carried out in the “zones of stable sticking” with a “positive” direction of the air flow to a vertical surface in the range $30^\circ \div 150^\circ$. The maximum values of sticking are achieved when the direction of air flow to a vertical surface at an angle $90^\circ$ (Figure 2) [6].

The process of removal of particles from vertical surfaces is carried out in the “zones of stable removal” with “negative” directions of air flow to a vertical surface in the ranges $0^\circ \div 20^\circ$ and $160^\circ \div 180^\circ$. The maximum values of the urban dust particles’ removal are when the air flow is along the vertical surface (Figure 2). With the values of air flow directions to a vertical surface in the ranges $20^\circ \div 30^\circ$ and $150^\circ \div 160^\circ$, which are called “transition zones”, partial adherence and detachment of dust particles occurs: ranges $25^\circ \div 30^\circ$ and $150^\circ \div 155^\circ$ are “zones of unstable sticking”, where the particles mainly adhere to the surface, ranges $20^\circ \div 25^\circ$ and $155^\circ \div 160^\circ$ are “zones of unstable removal”, where the particles predominantly come off the surface. However, under certain regimes of air flow rates, a slight removal of dust particles in the “zone of unstable sticking” is allowed to the vertical surface and slight sticking of dust in the “zone of unstable removal” on the vertical surfaces of buildings (Figure 2) [6].
We have obtained the formulas for calculating the current pollution, as well as predicting annual, seasonal and other dust pollution of the urban vertical surfaces made of various construction and finishing materials using the distribution of climatic factors such as air velocity and direction:

**Theoretical calculation of total sticking** atmospheric aerosol of the urban environment on vertical surfaces for a period of time \( \tau \) is carried out according to the following formula [6]:

\[
\Delta G_{\text{sticking}} = \sum_{i=1}^{3} \tau_i \int_{0}^{V_0} \gamma_{\text{Fmass}} \left( C_{,d,v,\phi} \right) \cdot C \cdot V \cdot \sqrt{1-\phi^2} dF(V)
\]

where \( \gamma_{\text{Fmass}} \) – is the mass fraction of sticking urban dust particles to dust in the air flow incident on the surface;
\( C \) – is the dust concentration in air, mg / m\(^3\);
\( V \) – is the air flow rate, m/s;
\( F(V) \) – is the integral distribution function of the wind speed.

Since the Weibull law is used to describe the air flow velocities' distribution in the work, its integral function and distribution density have the form:

\[
F(V,k,\beta) = 1 - e^{-\left(\frac{V}{\beta}\right)^k}; \quad f(V,k,\beta) = \frac{k}{\beta^k} V^{k-1} e^{-\left(\frac{V}{\beta}\right)^k},
\]

where \( k \) – is the distribution shape parameter;
\( \beta \) – is the distribution scale parameter.

**Theoretical calculation of removal** particulate matter from the urban vertical surfaces is carried out according to the formula (2) [6]:

\[
dG_{\text{removal}} = \gamma A_{\text{mass}} \cdot G dt
\]

where \( G \) – is the sticking density (value of a previously adhering dust layer on various vertical surfaces), decreasing value, mg / m\(^2\);
\( \gamma A_{\text{removal}} \) – defines the mass fraction of the urban dust particles that come off the surface under the influence of wind per unit time, a negative value for \( V=\text{const}, \phi=\text{const} \).

Based on theoretical calculations of the sticking and detachment of dust particles on urban vertical surfaces, 2 methods and a PC program for calculating the current pollution, as well as predicting the pollution of urban vertical surfaces depending on their location, environmental, climatic and other factors, have been developed. They are applicable to various buildings and structures made of such building and finishing materials as, for example, concrete, steel, glass, at the stage of their design and operation.
Methodology for calculating the current pollution of vertical surfaces of buildings and structures of the urban environment is designed for the existing facilities and characterizes their estimated pollution at the time of the survey. It is based on a sequential calculation of the structures’ dusting, and consists in a step-by-step calculation of the effects of winds in the “positive” or “polluting” range, which indicates the dust sticking to the vertical surfaces, and the “negative” range, which indicates the dust particles’ removal from the vertical surfaces, and also takes into account the values dust concentration in the air and its dispersed composition (Figure 2). Figure 3 shows a block diagram of a PC program operating on sequential pollution algorithms, which was developed based on this technique [6].

![Block diagram of the program for calculating the current pollution of buildings and structures](image)

**Figure 3.** Block diagram of the program for calculating the current pollution of buildings and structures

**Pollution Prediction Technique** of the buildings and structures’ vertical surfaces consists in a total calculation of future pollution of buildings and takes into account, on the basis of long-term observations, the order of influence of winds on the average in the “positive” range, which indicates dust sticking on the vertical surfaces, and the “negative” range, which indicates the dust particles’ removal from the vertical surfaces (Fig. 2). Fig. 4 shows a block diagram of a PC program operating on the total pollution algorithms, which was developed on the basis of this technique [6].

**Assessment of the contamination degree of the buildings and structures’ vertical surfaces.** To assess the buildings and structures’ pollution degree, it is necessary to take into account not only the physical aspect of the deterioration of their appearance, previously considered, associated with the building objects facades’ dusting, but also the visual aspect, covering the visual and psycho-emotional perception of a person by his environment, which helps to form a visual environment and is included in the field of visual ecology (video-ecology). To do this, we proposed a scale for assessing the appearance of buildings and structures made of various building and finishing materials. Its coloristic solution can be individually selected for any construction object (Figure 5).
Figure 4. Block diagram of a program for predicting the buildings and structures’ pollution

Figure 5. Rating scale for the buildings’ facades: a – for gray objects; b – for beige objects; c – for yellow objects; d – for burgundy objects

For example, Figure 5 shows a scale for visual assessment of the buildings’ facades, which is made in colors characteristic of the Tsaritsinsky’s objects (late XIX - early XX centuries) and Stalin periods (mid 1930s - 1950s) located in many areas of Volgograd and representing an extraordinary historical and cultural interest. According to this scale, the degree of pollution on the vertical surface is assessed according to a 10-point system, where No. 1 of the scale corresponds to the surface after cleaning or repair, № 10 of the scale – the pollution exceeds 70% of the entire vertical surface area. The facade is considered reasonably clean if the surface corresponds to the positions of scale № 1-5.

On the basis of the physical and visual aspects’ joint study of the buildings and structures’ pollution, a correspondence was established between the numerical values of the pollution of building objects by urban dust, obtained on the basis of the developed methods and program, as well as a scale characterizing the buildings vertical surfaces pollution visual perception degree. This allows a
comprehensive assessment of the buildings and structures facades’ condition, as well as the conclusion about the cleaning frequency.

Summary
The use of the developed methods and programs for calculating the current pollution, as well as predicting the pollution of urban vertical surfaces, determines the optimal frequency of their cleaning, avoiding damage and destruction. Comparison of the full-scale and calculated values of the density of dust sticking on the urban vertical surfaces showed that the calculated values are higher than the full-scale ones, including monthly values - no more than 10%, values for a year - no more than 7%. The methods have been successfully tested in the leading specialized organizations of Volgograd, Russia. The prevented economic damage, according to our calculations, is to save money by 2 or more times due to the optimally selected the cleaning frequency, cosmetic or maintenance of the buildings’ facade. This contributes to the visual environment formation that is comfortable for the population of the cities, because, from the standpoint of visual ecology, the deterioration of the appearance of construction objects negatively affects human health through its psycho-emotional perception of what they see. Thus, these studies contribute not only to the objects’ external appearance preservation of the urban environment made of various building materials that demonstrate the architectural and structural features of various historical periods of the country’s development, but also ensure the cities’ population health protection.

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