Features of Aerosols Solid Particles Movement with Various Densities inside Ventilated Airspace of the Cladding Façade Systems

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Abstract. This article presents the results of a study of aerosols solid particles movement inside ventilated air space of the ventilation façade. Particles of pollutants in the form of solid aerosol particles penetrate inside the air space of the ventilated façade. In the scientific literature, studies of settling processes (downward movement) of pollutant particles are given. However, the patterns of their movement inside the ventilated façade structure have not been studied thoroughly. The calculation method proposed by the author makes it possible to establish the speed of aerosol solid particles movement inside the ventilated air space of the ventilation façade and establish whether the particles will move upward together with the air flow or will settle on the structural elements of the ventilation façade facing the ventilated air space, taking into account the air flow rate and its temperature, and the size and density of aerosol contaminants.

1. Introduction
The air of large cities contains a large amount of various pollutants, the concentration of which is measured and recorded by automatic pollution control stations (APCS). For example, in Moscow there are 56 such stations, of which 3 are high-altitude stations on the Ostankino tower, 50 are stationary and 3 mobile stations, which monitor about 20 parameters of pollution - carbon oxides, nitrogen, sulfur dioxide, suspended particles of various sizes, etc. Their concentration in the air changes constantly. Figure 1 shows the dynamics of changes in the concentrations of individual pollutants in the conditions of Moscow[1-6].

Depending on the mass and size of the particle and the speed of wind impact, suspended particles of pollutants can rise up, fall down and hang in the airspace of the ventilation façade [7-10].

In the works [11-16], the movement of solid particles of aerosols settling down is considered. The resulting velocity formulas allow you to determine when the particles will fall down or hover in the air. However, these equations do not account for the air flow movement inside the airspace.
2. Methods of investigations
It is known that liquid particles, in particular, droplets of fog and clouds, anthropogenic, and natural dust, pollen, powdery materials have various shapes in the form of a ball, cylinder, plate, etc [17].

![Graph showing concentrations of pollutants in Moscow](image)

**Figure 1.** Dynamics of changes in the concentration of pollutants in Moscow.

In our calculations, based also on the data of [18], we will take a spherical shape of a dust particle. To solve this problem, it is required to find the speed of upward movement of aerosol solid particles in the air flow in the ventilated air space. We begin to solve this problem by determining the Reynolds criterion $Re$ depending on the speed of movement of a particle of pollutants.
Let us consider the movement of a spherical solid particle of aerosol in the ventilated air space of a ventilation facade, and determine particle with a diameter of 1.0 to 50 µm in a vertical air flow is determined by the equation (1) the Reynolds criterion for its various diameters. The Reynolds criterion for a moving parts of aerosol

$$\text{Re} = \frac{d_{p,d} v_{\text{air,ext}}}{\nu}$$  \hspace{1cm} (1)

where $d_{p,d}$ – aerosol particle diameter, m; $v_{\text{air,ext}}$ – air velocity in ventilated air space, m/c; $\nu$ – kinematic air viscosity, m$^2$/c.

The results of calculating the Reynolds number are shown in Table 1.

**Table 1.** Re-value as a function of air velocity and particle diameter of pollutants.

| $v_{\text{air,ext}}$ | 1,0 | 2,0 | 2,5 | 3,0 | 7,0 | 10 | 20 | 30 | 40 |
|---------------------|-----|-----|-----|-----|-----|----|----|----|----|
| Outdoor temperature $t_{\text{ext}}$ = -20 ºC |
| 0,1 | 0,008 | 0,017 | 0,021 | 0,025 | 0,064 | 0,086 | 0,172 | 0,258 | 0,344 |
| 0,2 | 0,017 | 0,034 | 0,043 | 0,051 | 0,129 | 0,172 | 0,344 | 0,517 | 0,689 |
| 0,3 | 0,025 | 0,051 | 0,064 | 0,077 | 0,193 | 0,258 | 0,517 | 0,775 | 1,034 |
| 0,4 | 0,034 | 0,068 | 0,086 | 0,103 | 0,258 | 0,344 | 0,689 | 1,034 | 1,379 |
| 0,5 | 0,043 | 0,086 | 0,107 | 0,129 | 0,323 | 0,431 | 0,862 | 1,295 | 1,724 |
| 0,6 | 0,051 | 0,103 | 0,129 | 0,155 | 0,387 | 0,517 | 1,034 | 1,551 | 2,068 |
| 0,7 | 0,060 | 0,120 | 0,150 | 0,181 | 0,452 | 0,603 | 1,206 | 1,810 | 2,413 |
| 0,8 | 0,068 | 0,137 | 0,172 | 0,206 | 0,517 | 0,689 | 1,379 | 2,068 | 2,785 |
| Outdoor temperature $t_{\text{ext}}$ = 0 ºC |
| 0,1 | 0,007 | 0,015 | 0,018 | 0,022 | 0,056 | 0,075 | 0,150 | 0,255 | 0,301 |
| 0,2 | 0,015 | 0,030 | 0,037 | 0,045 | 0,112 | 0,150 | 0,301 | 0,451 | 0,602 |
| 0,3 | 0,022 | 0,045 | 0,056 | 0,067 | 0,169 | 0,225 | 0,451 | 0,677 | 0,903 |
| 0,4 | 0,030 | 0,060 | 0,075 | 0,090 | 0,225 | 0,301 | 0,602 | 0,903 | 1,205 |
| 0,5 | 0,037 | 0,075 | 0,094 | 0,112 | 0,282 | 0,376 | 0,753 | 1,129 | 1,506 |
| 0,6 | 0,045 | 0,090 | 0,112 | 0,135 | 0,338 | 0,451 | 0,903 | 1,355 | 1,807 |
| 0,7 | 0,052 | 0,105 | 0,131 | 0,158 | 0,395 | 0,527 | 1,054 | 1,581 | 2,108 |
| 0,8 | 0,060 | 0,120 | 0,150 | 0,180 | 0,451 | 0,602 | 1,204 | 1,807 | 2,409 |
| Outdoor temperature $t_{\text{ext}}$ = 20 ºC |
| 0,1 | 0,006 | 0,013 | 0,016 | 0,019 | 0,049 | 0,066 | 0,132 | 0,199 | 0,256 |
| 0,2 | 0,013 | 0,026 | 0,033 | 0,039 | 0,099 | 0,132 | 0,265 | 0,398 | 0,531 |
| 0,3 | 0,019 | 0,039 | 0,049 | 0,059 | 0,149 | 0,199 | 0,398 | 0,597 | 0,797 |
| 0,4 | 0,026 | 0,053 | 0,066 | 0,079 | 0,199 | 0,265 | 0,531 | 0,796 | 1,062 |
| 0,5 | 0,033 | 0,066 | 0,083 | 0,099 | 0,249 | 0,332 | 0,664 | 0,996 | 1,328 |
| 0,6 | 0,039 | 0,079 | 0,099 | 0,119 | 0,298 | 0,398 | 0,796 | 1,195 | 1,593 |
| 0,7 | 0,046 | 0,092 | 0,116 | 0,139 | 0,348 | 0,464 | 0,929 | 1,394 | 1,859 |
| 0,8 | 0,053 | 0,106 | 0,132 | 0,159 | 0,398 | 0,531 | 1,062 | 1,593 | 2,215 |

The movement of solid particles of aerosols in the air flow will occur depending on the particle density $\rho_{p,d}$ and the air density $\rho_{\text{air,s}}$, as well as the velocities $v_{\text{air,s},p}$ and $v_{p,d}$, which is due to the action of the frontal force $R_s$. The movement of polluting aerosol particles is described by an equation of the form (described in [19]) by the equation

$$R_s - mg = m \frac{dv_{p,d}}{d\Theta}$$  \hspace{1cm} (2)

where $R_s$ - frontal force acting on an aerosol particle moving in the air flow of the ventilation facade.

Equation (2) was solved by the author and, taking into account the assumptions made, has the form
\[ v_{p,d} = v_{air,s} - \frac{gd^2}{18\rho_{air,s}} \]  

where \( v_{air,s} \) – air velocity in ventilated air space, m/c; \( g \) – acceleration of gravity m/c²; \( d_{p,d} \) – aerosol particle diameter, microns; \( \nu \) – kinematic air viscosity, m²/c; \( \rho_{p,d} \) – aerosol particle density, kg / m³ and \( \rho_{air,s} \) – air flow density, kg / m³.

The analysis of the calculation results according to the obtained equation (3) for moving solid particles of aerosols at small values of the Reynolds number made it possible to obtain the following regularity. The solid particles of aerosols that have gotten into the ventilated air space together with the outside air through the inlet into the ventilated air space rise upward under the influence of wind and gravitational pressure. In it, together with the air flow at a speed of 0.1 to 0.7 m/s, solid particles of aerosol with a diameter of 1.0 to 40 microns move up.

### Table 2. The speed of movement of solid particles of aerosols of various densities in the air space of a ventilated facade at different air velocities in ventilated air space and temperatures.

| Temperature, °C | Density, kg / m³ | Aerosol particle diameter, μm | 50 μm |
|----------------|-----------------|-------------------------------|-------|
|                |                 |                               | 0.1   | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  |
| 0              | 1000            | 0.03                          | 0.13  | 0.23 | 0.33 | 0.43 | 0.53 | 0.63 |
| -10            | 0.02            | 0.12                          | 0.22  | 0.32 | 0.42 | 0.52 | 0.62 |
| -20            | 0.02            | 0.12                          | 0.22  | 0.32 | 0.42 | 0.52 | 0.62 |
| -30            | 0.02            | 0.12                          | 0.22  | 0.32 | 0.42 | 0.52 | 0.62 |
| -40            | 0.01            | 0.11                          | 0.21  | 0.31 | 0.41 | 0.51 | 0.61 |
| 0              | 1500            | -0.01                         | 0.09  | 0.19 | 0.29 | 0.39 | 0.49 | 0.59 |
| -10            | -0.02           | 0.08                          | 0.18  | 0.28 | 0.38 | 0.48 | 0.58 |
| -20            | -0.02           | 0.08                          | 0.18  | 0.28 | 0.38 | 0.48 | 0.58 |
| -30            | -0.02           | 0.08                          | 0.18  | 0.28 | 0.38 | 0.48 | 0.58 |
| -40            | -0.03           | 0.07                          | 0.17  | 0.27 | 0.37 | 0.47 | 0.57 |
| 0              | 2000            | -0.05                         | 0.05  | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 |
| -10            | -0.05           | 0.05                          | 0.15  | 0.25 | 0.35 | 0.45 | 0.55 |
| -20            | -0.06           | 0.04                          | 0.14  | 0.24 | 0.34 | 0.44 | 0.54 |
| -30            | -0.06           | 0.04                          | 0.14  | 0.24 | 0.34 | 0.44 | 0.54 |
| -40            | -0.07           | 0.03                          | 0.13  | 0.23 | 0.33 | 0.43 | 0.53 |
| 0              | 2500            | -0.09                         | 0.01  | 0.11 | 0.21 | 0.31 | 0.41 | 0.51 |
| -10            | -0.09           | 0.01                          | 0.11  | 0.21 | 0.31 | 0.41 | 0.51 |
| -20            | -0.10           | 0.00                          | 0.10  | 0.20 | 0.30 | 0.40 | 0.50 |
| -30            | -0.11           | -0.01                         | 0.09  | 0.19 | 0.29 | 0.39 | 0.49 |
| -40            | -0.11           | -0.01                         | 0.09  | 0.19 | 0.29 | 0.39 | 0.49 |

Particles of aerosols that fall down are highlighted in red

3. Results of investigations
The performed calculations and analysis of the obtained values of the speeds of movement of aerosol suspended particles according to the expression (3) made it possible to establish that:
- solid aerosol particles with a diameter of 1-5 microns at a particle density of 500-2500 kg/m³ and the particles with a diameter of 10 microns with density of 500-1500 kg/m³ at an air flow rate in the ventilated air space up to 0.7 m/s move up at the same air flow rate in the ventilated air space;
- solid particles with a diameter of 20-30 microns at a particle density of 500-2500 kg/m³ move up in the airspace of the ventilation facade slightly slower than the air flow rate (at $v_{\text{air.s}} = 0.1 - 0.7$ m/s); 
- at low air velocities $v_{\text{air.s}} = 0.1$ m/s for aerosol particles with a diameter of 50 microns and a density of 1500-2500 kg/m³ and at $v_{\text{air.s}} = 0.2$ m/s for particles with a diameter of 50 microns and a density of 2500 kg/m³ at an air temperature of minus 30 and minus 40 °C, the gravitational head becomes greater than the wind pressure, which causes the movement of solid aerosol particles downward (table 2).

It means that at low air flow velocities in the ventilated space of the ventilation facade, solid aerosol particles of high density descend and settle on the surfaces of the ventilation facade structure - on the surfaces of brackets, fastening clamps, and heat-insulating material.

It should be noted that particles of pollutants are centers for condensation of water vapor. When the outside air temperature changes, the moisture in the air, including water vapor in the air space of the ventilation facade, can condense on the colder elements of the ventilation facade structures. Aerosol solid particles are centers of moisture condensation, on which droplets of condensation moisture are formed. Condensation moisture appears on the settled solid particles of aerosols, in which particles of pollutants - nitrogen dioxides and oxides, sulfur - dissolve. As a result, the formed acids of nitric and sulfuric acid negatively affect the metal elements of the ventilation facades, causing them to corrode. At the same time, an increase in the number of settled aerosol particles leads to the fact that the temperature of condensation formation increases and corrosion of the metal elements of the ventilation facade occurs at warmer values of the outside air temperature and smaller values of temperature fluctuations[20-22].

Taking into account the speed of the air flow in the airspace of the ventilation facade allows you to establish the presence of particles settling on the inner surfaces of the ventilation facade. The presence of particles in the air with a density of more than 1500 kg/m³ and a diameter 50 microns leads to their settling on surfaces, causing corrosion of metal elements of ventilation facades. Therefore, for regions in the presence of large aerosol particles in the air, it is necessary to especially carefully ensure the corrosion protection of the metal elements of the ventilation facades, primarily the bearing ones.

Based on the analysis, the obtained equation (3) allows us to take into account the physics of the process of moving solid suspended aerosols in the airspace of the ventilation facade. In contrast to the existing dependences, this expression allows one to determine not only solids velocity, but also the direction of movement - up or down. In contrast to the traditionally considered expressions describing only the settling of solid particles, the expression (3) is universal, allowing you to determine which particles will settle on the surfaces of the ventilation façade structural elements, and which will rise up along with the air flow into the ventilated air space of cladding facades.

4. Conclusions

As a result of the research, the following results were obtained:

1. The carried out theoretical studies and the developed methodology theoretically substantiate the process of settling of aerosol particles in the ventilated air space of ventilation facades, depending on the wind speed, mass and density of solid particles of aerosols;
2. On the basis of the performed calculations, the values of Reynolds numbers for solid particles of aerosols moving in the ventilated air space of ventilation facades under the influence of the Stokes force were obtained.
3. Regularities of movement of solid aerosol particles in the air space of cladding facades systems have been established. A universal equation has been obtained that makes it possible to calculate the speed of movement of aerosol solid particles in the air space of the ventilation facade up and down, depending on the air flow rate and its density in the ventilated space of the ventilation facade, as well as taking into account the density and size of solid particles.
5. References

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