Degree of Dust Dispersion in the Atmosphere under the Influence of Microclimatic, Topographical and Technical Factors

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Abstract

The process of dispersion of a component in a given medium such as air is determined by three groups of factors: microclimatic, topographical and technical. The shape of the emitted pollutant plume depends on the parameters of the emitter and the volume of the air masses. This article describes five types of plume: looping, conical, ventilating, tracing and contaminating. Vertical air stability is an important physical parameter of the atmosphere. Three states of this parameter are described in this paper: inversion, convection and isotherm. The degree of pollutant dispersion is influenced by air temperature, shaping physical and chemical processes that include coagulation, sorption and diffusion. Topographical factors include landform type, land cover and development. A significant number of obstacles interfere with the free flow of air through a given area. Technical factors relate to the emitter parameters (altitude, diameter) and the nature of its operation (time, temperature, speed of pollutants at discharge). Emissions can come from a large point-source emitter or from multiple diffuse emitters.

Meteorological factors were found to have a decisive influence, as climatic parameters are subject to the greatest changes due to atmospheric turbulence, vertical temperature gradient, wind effect and precipitation.

Keywords: *dispersion, dust contamination, physical parameters, atmosphere*

1. Introduction

Atmospheric air, in its natural state colourless and odourless, is a renewable resource sustained by the biological cycle in the biosphere. The atmosphere's self-cleansing capability involves the removal of pollutants through physical and chemical mechanisms. One example is high wind speeds, which diffuse and dilute pollutants, with the flow of cold air aiding in this process. Precipitation naturally removes pollutants from the air, depositing them on the ground. Through these phenomena, the concentration and toxicity of pollutants gradually decrease, and the environment returns to its clean state. However, human activities such as deforestation and the emissions of pollutants, energy and micro-organisms can disrupt this cycle and lead to atmospheric pollution. The air also disperses pollutants to various environmental components [7, 20, 25]. This process was described by Frederick Warner Holdgate in 1979.

Among the sources of pollution affecting the environment, four groups are distinguished: gases and vapours of chemical compounds, solid particles (both organic and inorganic), liquid droplets and microorganisms. Their unnatural occurrence or excess in the air indicates air pollution [2].

Atmospheric dispersion of dust occurs as soon as it is emitted. The cloud of pollutants escaping from the chimney consists of particles of varying sizes. Due to its mass, the dust may fall spontaneously to the surface. The varied size distribution of particle has a significant impact on the rate of deposition and the extent of movement in the atmosphere. Larger particles, those over 20 μm in diameter, settle faster. Particles with a diameter of 0.2 μm are deposited more slowly, making them subject to long-distance displacement, sometimes exceeding 1,000 km. Once dust particles reach the ground or water, they undergo sorption [8, 19]. Transboundary particles can make a significant contribution to the overall dust balance in an area [1].

The type of plume emitted depends on the parameters of the emitter and the air masses that interact with the pollutants. The literature describes five types of plumes (Figure 1) [16, 23]:

a) Looping type – in this case, the pollutant plume rises and falls due to wind speed and direction, depending on the height of the emitter. Pollutants spread rapidly and under downward currents may come into contact with the ground. This phenomenon usually occurs during the day with partial cloud cover and an unstable atmosphere;

b) Conical type – a cone-shaped form is observed that extends away from the emitter. Plumes occur when turbulence is weak and a state of near constant vertical equilibrium is maintained in the air. As the distance increases, the plume comes into contact with the ground. This phenomenon can occur at any time of day, with heavy cloud cover and high wind speeds;

c) Ventilating type – formed when a thermal inversion layer of air is located both below and above the high emitter source of pollutants. Under these conditions, the plume does not touch the ground, even over long distances, resulting in

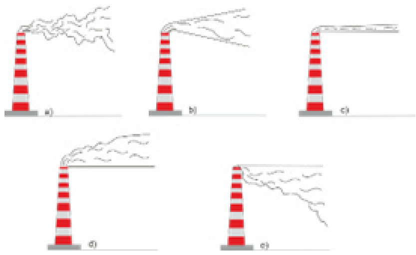

Fig. 1. Types of chimney plumes: a) looping, b) conical, c) ventilating, d) tracing, e) contaminating [23, modified]

Rys. 1. Rodzaje smug kominowych: a) pętlowa, b) stożkowa, c) wentylacyjna, d) trasująca, e) zanieczyszczająca [23, zmienione]

Tab. 1. Classification of the thermal and dynamic equilibrium states of the atmosphere according to Pasquill and Gilford [11]

Tab. 1. Klasyfikacja stanów termicznej oraz dynamicznej równowagi atmosfery według Pasquilla i Gilforda [11]

State of equilibrium of the atmosphere	Type of balance
1 (A)	Strongly unstable
2 (B)	Unstable
3 (C)	Slightly unstable
4 (D)	Indifferent
5 (E)	Slightly stable
6 (F)	Stable

low concentrations of pollutants, even for several days. The ventilating type arises most often at night or early morning, especially during fog. In the case of low emitters, there may be high concentrations of pollutants near the ground surface;

d) Tracing type – characterised by the lifting of the plume above the inversion layer. It forms when a temperature inversion occurs below the emission source, while above the source there is a thermal equilibrium transient. Under these conditions, pollutants are dispersed over long distances, with a low concentration of pollutants around the emitter, near the ground. The tracing plume forms most often in the morning and evening, when the inversion layer does not extend high, allowing pollutants to spread into the upper layers of the atmosphere;

e) Contaminating type – the most unfavourable type of plume, where the elevation of pollutants to the upper layers of the atmosphere is limited by a thermal inversion layer. Near the ground, unstable equilibrium conditions cause pollutants to accumulate. The contaminating type is most often observed early in the morning, when the rising sun dissipates thermal inversion layers and the fog lifts. During winter, high concentrations of pollutants can persist for several days, while in summer they are short-lived.

Dispersion, or the process of spreading a substance within a given medium such as air, leading to mass displacement, depends on three groups of factors: microclimatic, topographical and technical. Meteorological factors undoubtedly have a decisive influence, as climatic parameters are subject to the greatest changes as a result of atmospheric turbulence, vertical temperature gradients, wind effects and precipitation [4, 11, 17, 21].

Meteorological factors

Among the microclimatic factors affecting the degree of dispersion of pollutants, the vertical atmospheric equilibrium, defined by the difference between the actual vertical air temperature gradient and the dry-adiabatic or moist-adiabatic gradients, should be mentioned first and foremost. The degree of dispersion depends on the geographical location of the area under analysis, the season and the time of day. In practice, an extended classification of equilibrium states developed by Frank Pasquill and Daniel Gilford is used to determine the influence of the thermal and dynamic equilibrium of the atmosphere on the dispersion of pollutants, as shown in Table 1. This classification describes a spectrum from a highly unstable equilibrium to a stable equilibrium. A state of unstable equilibrium occurs when vertically displaced air continues to move in the same direction due to a higher temperature on ascent and a lower temperature on descent, i.e. when the vertical temperature gradient is greater than the dry-adiabatic and moist-adiabatic gradients. Neutral equilibrium is observed when the displaced air remains aloft due to the same temperature as the ambient temperature, i.e. when the vertical temperature gradient is equal to the dry-adiabatic gradient and the moist-adiabatic gradient. Stable equilibrium occurs when vertically displaced air returns to its original position, as the air temperature is lower on ascent and higher on descent. In this case, the vertical temperature gradient is smaller than the dry-adiabatic and moist-adiabatic gradients [10, 11, 24].

The vertical stability of the air is an important physical parameter of the atmosphere, with three states: inversion, convection and isotherm. Inversion occurs when the temperature near the surface is lower than that in the higher layers of the atmosphere. The literature [8] identifies the following types of inversions:

- Radiation inversions – most common at night and in winter when the ground surface quickly loses heat, cooling the adjacent atmospheric layers. This cooling increases air density and limits the spread of pollutants;
- Mechanical inversions – form during high-pressure systems when cold air descends, forming stable layers that make it difficult for air to mix. This phenomenon leads to an increased concentration of pollutants in the area;
- Frontal inversions – occur when warm air flows over cool air on the opposite side of the front. Such an arrangement is stable on both sides of the front and is conducive to increased concentrations of pollutants;
- Advection inversions – arise during the horizontal

Tab. 2. Values of the aerodynamic roughness factor z0 [18]

Tab. 2. Wartości współczynnika aerodynamicznej szorstkości terenu z0 [18]

No. (1)	Land cover type (2)	Factor z_0 (3)	No. (1)	Land cover type (2)	Factor z_0 (3)
1	Water	0.00008	8.2	- Medium-rise buildings	2.0
2	Meadows, pastures	0.02	9	City of 100,000 to 500,000 inhabitants	-
3	Arable fields	0.035	9.1	- Low-rise buildings	0.5
4	Orchards, thickets	0.4	9.2	- Medium-rise buildings	2.0
5	Forests	2.0	9.3	- High-rise buildings	3.0
6	Compact rural development	0.5	10	City of over 500,000 inhabitants	-
7	City of up to 10,000 inhabitants	1.0	10.1	- Low-rise buildings	0.5
8	City of 10,000 to 100,000 inhabitants	-	10.2	- Medium-rise buildings	2.0
8.1	- Low-rise buildings	0.5	10.3	- High-rise buildings	5.0

movement of air over a cool land surface or cool atmospheric layer. This results in a build-up of warm air over cool air and a deterioration in air quality.

Convection occurs when the air layer near the ground surface is warmer and less dense than that in the higher layers of the atmosphere. It is most prevalent in summer, when the ground heats up faster than the air. Warmer air rises while cooler, denser air falls, leading to vertical mixing of the layers. This process accelerates the dispersion of pollutants, allowing them to penetrate higher atmospheric levels. Isotherm arises when the temperature at 30 metres above the ground surface is constant. This phenomenon is common with heavy cloud cover, as clouds prevent the air layers from heating up near the ground surface. Isotherm also occurs in winter under clear skies, limiting the warming of lower atmospheric layers, often resulting in high pollutant concentrations near the ground. It is worth noting that the vertical stability of the air is determined by the temperature gradient, i.e. the difference between the ground surface temperature and the temperature at a height of 2 metres. A negative gradient indicates inversion, a positive gradient indicates convection and a gradient close to zero indicates isotherm [10].

Equally important is horizontal air movement, which includes wind speed, direction and turbulence. Horizontal movement occurs due to pressure differences over a given area. The degree of dispersion of pollutants takes into account the actual distributions of wind speeds and directions near the ground surface and the time of occurrence. It is assumed that pollutant concentration is inversely proportional to wind speed: as pollutants move away from the source of the emissions, some rise to the higher layers of the atmosphere, decreasing their quantity in the lower layers. Higher wind speeds favour a broader spread of pollutants. The pollutant plume moves with the speed of the surrounding air masses, and a change in their direction results in a change in the movement of the pollutants. As a result of atmospheric turbulence and mixing of the cloud with the surrounding air, its volume gradually increases, and the concentration of pollutants decreases as the cloud moves away from the emission source. A semi-cone-shaped cloud with its apex at the emission point is usually observed. The most unfavourable conditions occur at low wind speeds (below 2 m/s) and during wind silences [10, 16].

Air temperature influences the physical and chemical processes in the atmosphere. These processes include coagulation, sorption and diffusion. The temperature difference between the emitted pollutants and the ambient air plays a significant role. In winter, temperature distribution near the ground surface is especially important for pollutant dispersion: hot gases rise faster in a cold environment due to the density difference. This results in a better dispersion of pollutants, but at the same time favours chemical reactions between airborne substances [3, 9]. A 2020 study in China showed that higher air temperatures favour a reduction in concentrations of pollutants, especially at higher altitudes. However, in some regions, such as northern China, higher temperatures have contributed to higher concentrations of pollutants. This phenomenon is very complex, and influenced by microclimate and local conditions. Additionally, high temperatures promote more intense evaporation, leading to an increase in relative humidity levels, which are responsible for air quality [14].

Pressure systems significantly impact air pollution levels. During low-pressure systems, the air rises, which favours the spread of pollutants. There is often high cloud cover, which stabilises the state of the atmosphere, but also limits the heating of the land surface during the day and cooling at night. High-pressure systems, on the other hand, are characterised by denser, descending air that forms an inversion layer, limiting air exchange. Stable conditions under high pressure favour surface warming during the day and rapid cooling at night. Areas in basins, such as Krakow, are particularly susceptible to cold air stagnation, which favours the formation of inversions. The presence of a river or other bodies of water lead to fog formation, exacerbating this phenomenon [8].

Another element is relative humidity, which is the percentage ratio of the current amount of water vapour in the air to the maximum possible amount of water vapour the air can contain at a given temperature. Numerous studies have observed that, under conditions of increased humidity, dust particles aggregate into larger particles and reduce the amount of dust in the environment. In contrast, the results of dust deposition measurements in Beijing (2014-2015) showed that high humidity reduces deposition speed, as mentioned in the next section [9, 18, 26]. It should be noted that the activity of some gaseous compounds, e.g. sulphur oxides, increases with higher water vapour content in the air. If the relative humidity exceeds 70%, there is a noticeable acceleration in the conversion of SO2 to sulphuric acid in the atmosphere. This conversion occurs during vapour condensation, but also in the presence of catalysts such as iron, copper or manganese [22].

As with atmospheric humidity, precipitation acts as a natural atmospheric cleansing phenomenon that reduces concentrations of pollutants. The diameter of the raindrops plays an important role in cleansing dusty air; droplets with

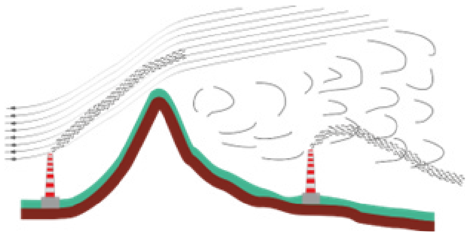

Fig. 2. Schematic of the effect of the hill on the spread of the plume of pollutants [22, modified]
Rys. 2. Schemat wpływu wzgórza na rozprzestrzenianie się smugi zanieczyszczeń [22, zmienione]

a diameter of 0.45 mm provide the best cleansing properties. Snowfall also improves air quality due to its large absorptive surface and low settling velocity [9].

Topographical factors

Another group of factors which have an impact on the spread of pollutants in the air includes topographic features such as terrain type, surface cover and land use. The exact parameters of the aerodynamic roughness factor z0 are determined based on data (Table 2) contained in the Regulation of the Minister of the Environment of 26 January 2010 on reference values for certain substances in the air, according to formula (1) [18, 22].

$$z_0 = \frac{1}{F}\sum_c F_c * z_{0c} \quad (1)$$

Where: z_0 – average value of the aerodynamic roughness factor in the calculation area, m; F – area of the calculation area, m^2; c – number of the area with the given land cover type, –.

Topographical factors can have a direct impact on the value of microclimatic factors (local impact, on a small scale near terrain obstacles) and an indirect impact (regional impact, on a large scale). When a plume of pollutants encounters terrain obstacles, wind speed and direction are disrupted. An example of interference is shown in Figure 2, where the plume encounters an obstacle such as a hill. The streams flow at high speed over the hill, undergo strong turbulence and then decelerate rapidly behind the obstacle, creating an aerodynamic shadow. In the aerodynamic shadow there is limited ventilation, resulting in a deterioration of air quality. The length of the aerodynamic shadow is assumed to be equal to six times the height of the obstacle. A high number of obstacles can completely disrupt the airflow and thus limit the dispersal of pollutants beyond the area [6, 10, 22].

Worth noting is the effect of woodland on the cloud of pollutants. In the vicinity of a forest, the plume rises above the tree canopy, where the irregular surface of the treetops causes air vortices, allowing pollutants to penetrate the forest interior. This is why green belts are so important in dispersing pollutants. Thanks to phytoncides (chemical compounds with bactericidal, fungicidal and protozoal properties) released by plants, it is possible to reduce harmful pollutants in the air. It is assumed that a deciduous forest can release up to 20 kg of phytoncides per hectare in 24 hours [10].

Technical factors

Technical factors are directly related to the parameters of emitters (altitude, diameter) and their operating characteristics (operating time, temperature and speed of pollutants at discharge). The type of emission plays a major role: whether it comes come from a single large point emitter (high emission) or from multiple dispersed sources (low emission) and uncontrolled emissions from the burning of solid fuels. Therefore, maintaining equipment in good condition, inspecting it regularly, using environmentally friendly technologies and equipment and using appropriate methods to neutralise pollution are essential. Cyclones and electrostatic precipitators are most commonly used for dust removal. For the elimination of very small particles, in addition to electrostatic precipitators, it is necessary to use wet dust extraction or filtration techniques. All technical factors determine the amount of pollutants emitted into the natural environment [6, 11, 12].

Summary

The degree of pollutant dispersion in the air depends on the geographical location of the study area, season and time of day. It was found that the meteorological factors have the biggest impact on the degree of dispersion. Air temperature shapes the physical and chemical processes in the atmosphere (coagulation, sorption, diffusion), and the temperature difference between the emitted pollutants and the ambient air plays a major role. Equally important is horizontal movement of the air, i.e. the speed, direction and turbulence of the wind. Horizontal movement occurs because of pressure differences in a given area, and pressure systems determine the state of air pollution. Precipitation, as a natural atmospheric cleansing phenomenon, has the effect of reducing pollutant concentrations. Topographical factors – such as terrain type, surface cover and land use – have an indirect impact on the dispersion of pollutants in the air. Technical factors relate to the physical characteristics of the pollutant emitter (altitude, diameter) and its operating characteristics.

Human activities and the associated dust emissions lead to numerous negative changes in the natural environment. The environmental burden includes both direct and indirect effects. Direct effects include reduced atmospheric air quality, a reduction in insolation due to the high concentration of dust in the air. Indirect effects include deterioration in the health and well-being of the population, deterioration in the aesthetics of the landscape, degradation of soils, and material losses associated with the maintenance of building materials [5, 13, 15].

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Stopień dyspersji pyłów w atmosferze pod wpływem czynników mikroklimatycznych, topograficznych i technicznych

Proces rozpraszania składnika w danym ośrodku, jakim jest powietrze, jest uwarunkowany trzema grupami czynników: mikroklimatycznymi, topograficznymi oraz technicznymi. Kształt wyemitowanej smugi zanieczyszczeń zależy od parametrów emitora oraz od objętości mas powietrza. W artykule opisano pięć typów smug: pętlowy, stożkowy, wentylacyjny, trasujący i zanieczyszczający. Pionowa stateczność powietrza jest ważnym parametrem fizycznym atmosfery. W pracy zostały opisane trzy stany tego parametru: inwersja, konwekcja i izotermia. Na stopień dyspersji zanieczyszczeń wpływa temperatura powietrza, kształtująca procesy fizyczne oraz chemiczne, do których należą koagulacja, sorpcja oraz dyfuzja. Do czynników topograficznych zalicza się typ ukształtowania terenu, jego pokrycie oraz zagospodarowanie. Duża liczba przeszkód zaburza swobodny przepływ powietrza przez dany obszar. Czynniki techniczne dotyczą parametrów emitora (wysokość, średnica) oraz charakteru jego pracy (czas, temperatura, prędkość zanieczyszczeń na wylocie). Emisja może pochodzić z dużego emitora punktowego lub z wielu rozproszonych emitorów. Stwierdzono, że decydujący wpływ mają czynniki meteorologiczne, gdyż parametry klimatyczne podlegają największym zmianom w wyniku turbulencji atmosfery, pionowego gradientu temperatury, działania wiatru i opadu atmosferycznego.

Słowa kluczowe: *dyspersja, zanieczyszczenia pyłowe, parametry fizyczne atmosfery*