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The formation regularities of aerosols resulting from arc welding of main gas pipelines

Reguły tworzenia się aerozoli podczas spawania łukowego głównych gazociągów

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ABSTRACT: The oil and gas industry is characterized by the presence and operation of various high-risk facilities, which contribute to occupational injuries and diseases, as well as environmental pollution. Among these, pipeline systems – particularly main gas pipelines – are prominent. The purpose of this research is to study the processes involved in the manual arc welding of main gas pipelines during construction and repair, which adversely affect human health and the environment. Gas pipeline welding during construction and repair is performed both in semi-enclosed spaces and in the open air. In both cases, manual arc welding is predominantly used due to its mobility and ease of implementation. The equipment required for arc welding is much cheaper and simpler than that used for laser, electron beam, or hybrid welding. These advantages have led to the widespread use of arc welding across various industries. However, manual arc welding has a considerable negative impact on human health and the environment due to the emissions of toxic substances in the form of welding aerosols. The regularities of aerosol formation during arc welding and the mechanisms of their distribution in the environment are examined, enabling the planning of welding operations in a way that reduces the risk of occupational diseases. Empirical correlations were obtained to determine the concentrations of harmful substances. It was shown that an aerosol cloud, dispersed by wind, spreads with particles diffusing in all directions, leading to a rapid decrease in concentration. It was found that during the welding of pipes under moderate wind conditions, aerosol smoke from a point source spreads in the air in a conical torch shape, expanding both vertically and horizontally. It is substantiated that the main physical process involved is diffusion combined with heat transfer due to convective airflows. Based on Sutton's modified mathematical model, it was established that during the welding of above-ground pipelines under laminar wind conditions, aerosol smoke mixes with air solely through molecular diffusion, whereas during underground welding, aerosol dispersion is caused by the physical processes associated with the formation of a welding torch.

Key words: arc welding, gas pipelines, aerosol, diffusion, turbulence.

STRESZCZENIE: Przemysł naftowy i gazowniczy cechuje się obecnością i eksploatacją różnych obiektów wysokiego ryzyka, co wiąże się z występowaniem urazów zawodowych i chorób, a także z zanieczyszczeniem środowiska. Wśród tych obiektów szczególnie istotne są systemy rurociągowe, zwłaszcza główne gazociągi. Celem niniejszych badań jest analiza procesów zachodzących podczas ręcznego spawania łukowego głównych gazociągów w trakcie ich budowy i napraw, które mają istotny wpływ na zdrowie ludzi i stan środowiska naturalnego. Spawanie gazociągów podczas budowy i napraw odbywa się zarówno w przestrzeniach półzamkniętych, jak i na wolnym powietrzu. W obu przypadkach stosuje się głównie ręczne spawanie łukowe ze względu na jego mobilność i łatwość zastosowania. Sprzęt niezbędny do spawania łukowego jest znacznie tańszy i prostszy niż ten wykorzystywany do spawania laserowego, wiązką elektronów czy metodami hybrydowymi. Te zalety sprawiają, że spawanie łukowe jest szeroko stosowane w różnych gałęziach przemysłu. Niemniej jednak, ręczne spawanie łukowe ma znaczący negatywny wpływ na zdrowie człowieka i środowisko ze względu na emisję substancji toksycznych w postaci aerozoli spawalniczych. W pracy omówiono prawidłowości tworzenia się aerozoli podczas spawania łukowego oraz mechanizmy ich rozprzestrzeniania się w środowisku, co pozwala na planowanie prac spawalniczych w sposób ograniczający ryzyko chorób zawodowych. Uzyskano empiryczne zależności umożliwiające określenie stężeń substancji szkodliwych. Wykazano, że chmura aerozolu rozpraszana przez wiatr rozprzestrzenia się z cząstkami dyfundującymi we wszystkich kierunkach, co prowadzi do szybkiego spadku stężeń. Stwierdzono, że podczas spawania rur w warunkach umiarkowanego wiatru, dym aerozolowy ze źródła punktowego rozprzestrzenia się w powietrzu w formie stożkowego strumienia, rozszerzającego się zarówno pionowo, jak i poziomo. Wykazano, że głównym procesem fizycznym jest dyfuzja połączona z przenoszeniem ciepła na skutek konwekcyjnych przepływów powietrza. Na podstawie zmodyfikowanego modelu matematycznego Suttona ustalono, że podczas spawania rurociągów

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naziemnych w warunkach wiatru laminarnego, dym aerozolowy miesza się z powietrzem wyłącznie poprzez dyfuzję cząsteczkową, natomiast w przypadku spawania podziemnego dyspersja aerozoli jest spowodowana procesami fizycznymi związanymi z formowaniem się łuku spawalniczego.

Słowa kluczowe: spawanie łukowe, gazociągi, aerozol, dyfuzja, turbulencja.

Introduction

The modern development of society is marked by worsening environmental conditions due to the increasing level of human impact. This progressive phenomenon leads to the degradation of all components of the environment, posing a threat to sustainable development and raising questions about the very existence of humanity. In recent years, there has been a rise in studies on household (Malovanyy et al., 2018; Karpuzcu et al., 2020; Singh et al., 2023) and industrial (Shmandiy et al., 2017) wastewater, as well as the utilization of solid industrial and household waste (Tulaydan et al., 2017, Popovych et al., 2018; Kryvenko et al., 2019; Khan and Madhukar, 2023). Researchers are also focusing on minimizing gas emissions (Vasyliv and Semchuk, 2019; Kryvenko, 2021). We focused our attention on studying the regularities of aerosol formation resulting from arc welding of main gas pipelines. By understanding these regularities, it is possible to plan welding operations in a way that reduces the risk of occupational diseases among workers and minimizes environmental pollution.

Welding of main gas pipelines during repair and construction is carried out both in the semi-enclosed spaces (underground pipelines) and in open areas (above-ground gas pipelines). In both cases, manual arc welding is mostly used, which may have a significant adverse impact on the human body due to the emission of harmful substances, as the distance between the welding point and the welder is only 20–30 cm. The magnitude of impact depends on the type of electrode coating (basic or cellulose) and the welding method (electrocontact, submerged arc welding, shielded arc welding, etc.).

Hazardous substances released during welding form aerosols in the air. The dispersion of aerosols in the air requires special consideration, which can be addressed through mathematical modeling of processes such as convective transfer, longitudinal and transverse dispersion, and diffusion.

The regularities of aerosol formation resulting from arc welding in the machine-building and chemical industries and their environmental dispersion are covered in the works of Popović et al. (2014), Norhidayah et al. (2024), and Gupta et al. (2024). However, the modeling of welding aerosol dispersion during manual welding of gas pipelines has not yet been sufficiently studied.

During the welding of main gas pipelines, the behavior of aerosol clouds in the atmosphere depends significantly on meteorological factors. The shape of the aerosol cloud is influenced primarily by the location, type, and configuration of the emission source.

This paper examines linear sources (pipes) which consist of a number of point sources (welding spots) located along a straight line.

During pipe welding in mild wind conditions, aerosol fumes from a point source spread in the air in a long, cone-shaped torch that expands both vertically and horizontally.

When viewed from above, at some point the torch takes the form shown in Figure 1 (hatching) (Beketov et al., 2011). It swings from side to side and, within minutes, can cover the area between the dashed lines. If instant sampling of smoke is conducted at points along the straight line AB and a distribution curve is plotted in the transverse section of the torch, a CDE curve with a high peak and narrow base is obtained. However, if continuous sampling is performed at the same points over several minutes, the transverse concentration profile FGH becomes much wider and lower. In this paper, we refer to these time-averaged values of concentration.

Under laminar wind conditions, smoke would mix with air only due to molecular diffusion, and the degree of cloud dispersion would be extremely limited. However, natural wind is typically turbulent and is characterized by numerous randomly moving vortices of varying length, ranging from a few centimeters (Mandryk et al., 2014, Mandryk and Mykhailiuk, 2016).

A valid interpretation of the nature of vortices has yet to be established. Modern meteorology attempts to describe their structure through relationships between turbulent velocities at different times or spatial points. However, for our purposes, it is more practical to view vortices as air volumes that, like gas molecules, transport mass, momentum, and heat from one spatial point to another through continuous mixing with the surrounding air. If a vortex is indistinguishable from the surrounding air mass, it is considered completely dissolved in the atmosphere. Thus, the aerosol cloud, as it spreads downwind, is continuously dissipated, with particles diffusing in all directions, resulting in a rapid decline in concentration.

Turbulence in the lower layers of the atmosphere is caused by both mechanical and thermal processes. As layers of air rub against the Earth's surface, they create wind gusts. Thermal turbulence arises from the instability of air layers that receive heat from the sun-heated ground. Turbulence in the lower atmospheric layers is largely influenced by the time of day, cloud cover, and landforms. If the lower layers of air neither gain nor lose heat, then the temperature changes insignificantly

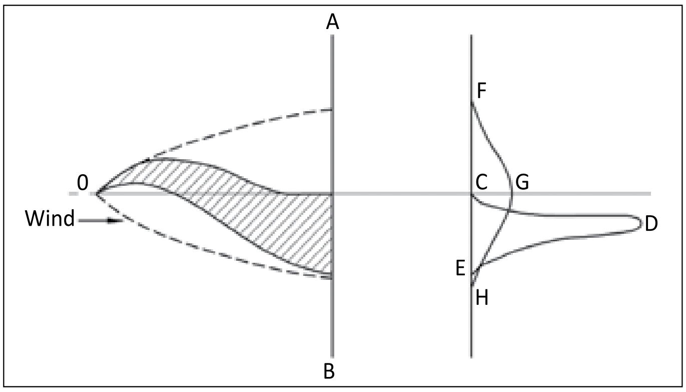

Figure 1. Instant (CDE) and time-averaged (FGH) profiles of aerosol cloud concentrations resulting from a continuous point source (created by the authors based on the concept proposed in Beketov et al. (2011), with further development and adaptation to the context of this study)

Rysunek 1. Natychmiastowe (CDE) i uśrednione w czasie (FGH) profile stężeń chmur aerozolu wynikające z ciągłego źródła punktowego (opracowane przez autorów na podstawie koncepcji zaproponowanej w pracy Beketov i in. (2011), z dalszym rozwinięciem i dostosowaniem do kontekstu niniejszego badania)

with altitude, and the atmosphere is in a state of neutral equilibrium (Bakharev et al., 2016).

To transition from purely qualitative descriptions to a quantitative theory of turbulent scattering in the lower atmosphere, an appropriate mathematical tool is required. This tool must correlate with measurable values, which are primarily influenced by mechanical factors under known meteorological conditions in the lower atmosphere. As solar heating intensifies, atmospheric stability is disrupted, the temperature gradient with altitude increases, and turbulence grows significantly. The temperature gradient at which smoke dissipates rapidly in all directions typically occurs on clear days, beginning about an hour after sunrise and ending about an hour before sunset. On clear, calm nights, thermal radiation from the Earth's surface causes an inversion of the temperature gradient, during which atmospheric turbulence is minimal and smoke dispersion is significantly reduced.

Thus, the degree of atmospheric turbulence near the Earth's surface shows clear diurnal variations. Given the average vertical temperature gradient and wind speed, a dimensionless function known as the Richardson number can be determined. According to experimental data, this number, rather than the individual meteoritical factors alone, determines the degree of turbulence.

Turbulence manifests as fluctuations in wind speed relative to the mean value. These fluctuations are further amplified by obstacles in the wind's path, such as trees, buildings, and uneven terrain. Prominent topographical features (hills, valleys, cities) can generate large, steady vortices. When the sun heats a valley, air moves up the slopes and then descends into the valley center. Later, the upslope wind weakens. Due to evening cooling of the air near the upper slopes, a "katabatic" circulation develops. In such cases, airflows downward along the slopes, and if there is a source of industrial emissions in the valley, this may result in substantially high local concentrations of air pollutants.

This knowledge can be used to calculate the concentration and other properties of the aerosol cloud at any given point. Although a fully satisfactory theory of turbulent diffusion has not yet been developed, several approximate models and computational approaches are available (Popov et al., 2019; Starchak et al., 2010).

Materials and methods

This paper analyzes the results of experimental studies on aerosols formed during the use of various electrodes, conducted at the State Institution Kundiiev Institute of Occupational Health of the National Academy of Medical Sciences of Ukraine. According to the experimental data (Yushchenko et al., 2009), the specific amount of dust (solid phase of aerosol) formed when using different electrodes is as follows: 18.6–36.5 g/kg of welding material for electrodes with ore-type (manganese) coatings, 11.3–13.5 g/kg for basic (fluorite-calcium) coatings, and 7.1–15.3 g/kg for rutile or rutile-carbonate coatings. The main aerosol components are iron oxides (45–65%). However, depending on the electrode type, aerosols also contain oxides of manganese, chromium, cadmium, vanadium, zinc, lead, silicon dioxide, and fluoride compounds. Although the concentrations of these substances are relatively low compared to iron oxides, their toxicity makes them critically important in determining the overall harmfulness of welding dust.

The total content of dust, manganese oxides, fluoride, and chromium-containing compounds in the working zone depends on the composition of the welding metal, the electrode core and coating, the electrode diameter, and the technological parameters of the welding process (welding current, arc voltage, current type and polarity, welding speed). Additional influencing factors include the welder's position relative to the arc, the configuration of the welded components (which determines accessibility of welding elements and the convenience of performing the work), and the effectiveness of dust control measures such as ventilation systems and personal protective equipment.

Laboratory experiments (Yushchenko et al., 2009) have demonstrated that the amount of manganese in welding dust is proportional to the manganese content in the electrode coating. The smallest proportion of manganese oxides is found in aerosols produced by fluoride-calcium and rutile-coated electrodes, while the highest is found in aerosols from manganese-coated electrodes. Manganese oxides in welding aerosols are potentially hazardous due to their ability to cause manganese intoxication. To mitigate this effect, electrodes with reduced manganese content or alternative low-toxicity materials (particularly rutile-coated electrodes) are increasingly being used instead of high-manganese electrodes.

Although calcium fluoride-coated electrodes result in lower manganese oxide emissions, they release fluoride compounds (hydrogen fluoride, tetracyclic silicon, etc.) in concentrations that may be significant in the welder's breathing zone.

Welding with chromium-plated electrodes is associated with significant aerosol contamination of the breathing zone (solid particle emissions ranging from 10.65 to 30 g/kg). From a hygienic standpoint, a key concern is that chromium oxides concentrations vary significantly depending on welding conditions. The proportion of the more toxic heavier chromium compounds in the welding dust is 2.5–3.5 times higher than that of trivalent chromium compounds. Silicon dioxide in welding dust accounts for 0.9–1.8%.

In the works of Kurovets et al. (2011) and Levchenko et al. (2021), the methodology for calculating the concentration of harmful substances in the weld area is improved based on data on the formation intensity of welding aerosols. Specifically, the content of chromium compounds in welding aerosols does not depend on the chromium content of the base metal, while the concentration of manganese does depend on it and increases by 10–15% when its content in the deposited metal rises from 0.6 to 34%. At the same time, an increase in chromium content in the base metal leads to a reduction in the emission level of welding aerosols by approximately 20%, without a noticeable change in toxicity. In contrast, an increase in manganese content in the base metal leads to approximately 1.5-fold increase in both the emission level and the toxicity of welding aerosols. According to Bezushko et al. (2021), the concentrations of manganese, chromium, and nickel in welding aerosols are determined primarily by their content in the electrode material and the volatility of their vapors at temperatures typical of metal melting points. Thus, the authors conclude that the radiation level of welding aerosols depends not only on the arc power (voltage) but also on the manganese content in the base metal. Manganese exhibits high vapor pressure at weld batch temperatures, and manganese vapors above the weld bath contribute to scattering of the melted and evaporated electrode material.

Despite the implementation of various measures to mitigate hazardous and harmful production factors, the number of occupational disease cases among welders in Ukraine continues to increase by 60–100 individuals annually (Polukarov, 2005).

The creation of favorable and safe working conditions in the welding industry, especially for manual arc welding, is directly dependent on providing workers with protective equipment that reduces exposure to harmful factors in the workplace. The development of methods for modeling the aerosol dispersion aimed at reducing the risk of occupational diseases remains a relevant scientific and technical challenge.

Results and discussion

The first models of impurities distribution in the atmosphere appeared in the mid-20th century, although the theoretical foundations for such models were laid earlier in the 1920s and 1930s. These models were based on studies of near-surface meteorological elements in the atmospheric boundary layer and on the observation that the processes of heat transfer, momentum exchange, and impurity dispersion exhibit similar behavior and can be used while simulating these processes.

At the initial stage of constructing models describing the diffusion of impurities in the atmosphere, two approaches were distinguished. The first, based on the diffusion equation for turbulent flow with constant coefficients, is described in the works of Roberts (1961). The second approach, based on a statistical description of the impurity concentration spreading process, was proposed by Berlyand (1991). Here, the admixture distribution near the point source – namely, the point of manual welding in the open air – follows the Gaussian distribution law:

$$C(x,y,z,\tau)=\frac{M\left(\tau-\frac{x}{U_a}\right)}{2\pi U_a\cdot\tau\cdot\sigma_Z(x+x_{vZ})\cdot\sigma_y(x+x_{vy})}\cdot\left[exp-\left(\frac{y^2}{2\left(\sigma_y(x+x_{vy})\right)^2}\right)\right]\cdot\left[exp-\left(\frac{(z-h_0)^2}{2\left(\sigma_z(x+x_{vZ})\right)^2}\right)\right] \quad (1)$$

where:
C – concentration of welding aerosol [g/m^3],
x, y, z – coordinates,
τ – time [s],
M – mass of aerosol discharged into the atmosphere [g/s],
U_a – wind speed [m/s],
σ_z– standard deviation of vertical dispersion [m],
σ_y – standard deviation of horizontal dispersion [m],
x_{vz}, x_{vy} – distance from the source of emissions [m].

The solution of equation (1) is obtained under the initial and boundary conditions, $C(\tau = \tau^*, x = x_0, y = 0, z = h_0)$.

Thus:

$$C = \frac{M\left(\tau^* - \frac{x}{U_a}\right)}{2\pi U_a \cdot \tau^* \cdot \sigma_Z(x_0 + x_{vZ}) \cdot \sigma_y(x_0 + x_{vy})} \quad (2)$$

According to the given formula, it is possible to find out the concentration of harmful substances at a certain time (τ*) in the zone corresponding to the height of the welding torch (h_0).

Two expressions derived by Berlyand (1991) allow the determination of the concentration of aerosol generated in the smoke of a welding torch, % [g/cm^3], at this point in the cloud, provided that the emission rate of the substance (electrode material and welding wire) and certain meteorological data are known.

A continuous point source located at ground level, with a productivity, Q [g/s], gives the aerosol concentration as:

$$\chi_\tau(x,y,z) = \frac{2\cdot Q}{\pi\cdot C_y\cdot C_z\cdot\tilde{u}\cdot x^{2-n}} exp\left[-x^{n-2}\cdot\left(\frac{y^2}{C_y^2}+\frac{z^2}{C_z^2}\right)\right] \quad (3)$$

where:

x, y, z – spatial coordinates, m (the source is at the origin), corresponding to directions along the wind, across the wind, and vertical to the surface, respectively,

$\tilde{u}$ – average wind speed [m/s],

C_y and C_z – generalized coefficients of turbulent diffusion,

n – a parameter whose numerical value varies between 0 and 1 depending on atmospheric stability (Sutton, 1953); with n = 1/5 for strong instability; n = 1/4 under neutral conditions; n = 1/3 for moderate inversion; and n = 1/2 for strong inversion.

Figure 2 shows the calculated distribution of aerosol concentration from the welding point on the surface as a function of the coordinates x and y, based on the following initial parameters: Q = 10 g/s; C_y = 10; C_z = 10; $\tilde{u}$ = 5 m/s; n = 1. The change in aerosol concentration [g/cm^3] on the surface upwards as a function of the coordinates x and z for the given values of the generalized turbulent diffusion coefficients is shown in Figure 3.

An infinitely long linear source, located perpendicular to the direction of the wind, with productivity Q [g/(s · cm)] gives:

$$x_l(x,z) = \frac{2\cdot Q}{\pi^{1/2}\cdot C_z\cdot\tilde{u}\cdot x^{1-n/2}} exp\left[-\frac{z^2}{C_z^2\cdot x^{2-n}}\right] \quad (4)$$

The integration of both parts of equations (3) and (4) over time gives the relation between the total amount of material released by the source over a certain period of time and the mass of the substance collected during the continuous flow of smoke through the filter at a given point during this time. These ratios are valid whether the source's productivity is constant over time or not, and are useful in practice, since it is easier to measure the total increment of the filter than the concentration. Another useful conclusion is that the integrated concentration over y from $-\infty$ to $+\infty$ from the point source with productivity Q is numerically equal to the concentration at the same distance from the linear source with the productivity Q [g/(s · cm)].

According to these equations, the concentration is directly proportional to the productivity of the source and inversely proportional to the wind speed. Measurements in smoke clouds have confirmed that for a point source, the distribution of

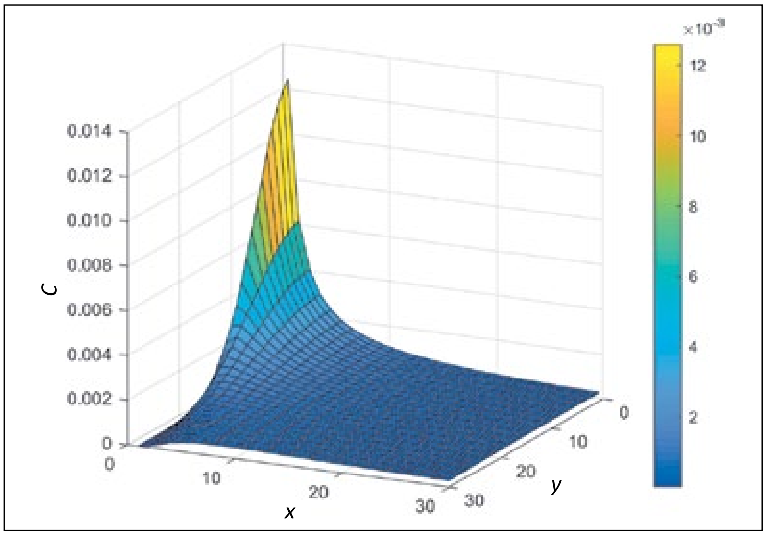

Figure 2. Change in aerosol concentration, C [g/cm^3], on the surface as a function of the coordinates x and y at given values of the generalized turbulent diffusion coefficients

Rysunek 2. Zmiana stężenia aerozolu, C [g/cm^3], na powierzchni w funkcji współrzędnych x i y przy danych wartościach uogólnionych współczynników dyfuzji turbulentnej

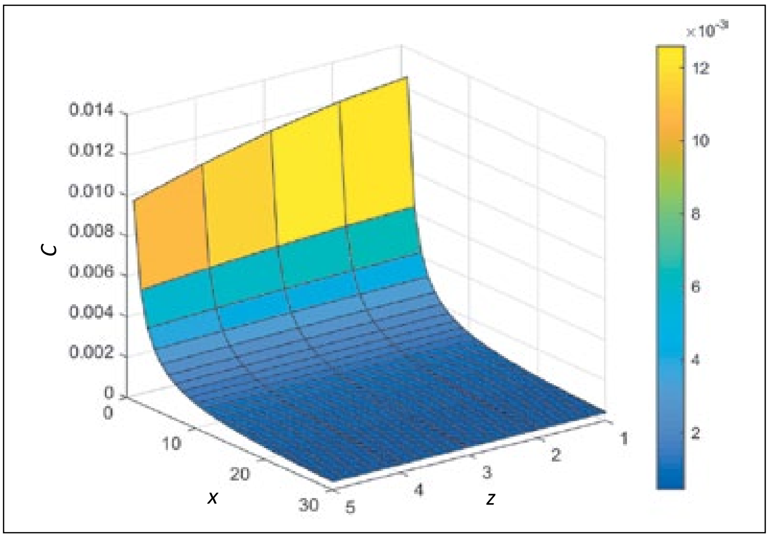

Figure 3. Change in aerosol concentration, C [g/cm^3], on the surface upwards as a function of the coordinates x and z for the given values of the generalized turbulent diffusion coefficients

Rysunek 3. Zmiana stężenia aerozolu, C [g/cm^3], od powierzchni ku górze w funkcji współrzędnych x i z przy danych wartościach uogólnionych współczynników dyfuzji turbulentnej

concentration in transverse and vertical directions is approximately expressed by the Gaussian curve. The only difference is that, due to reflection from the Earth's surface, the vertical distribution corresponds to only one half of this curve (Beketov and Evtukhova, 2017). From equations (3) and (4), where $n = ¼$ corresponds to diffusion over grass equal to the increase in the adiabatic gradient, the maximum concentration (corresponding to $y = z = 0$) should decrease with the distance in the direction of the wind as $x^{-1.75}$ for the point source and as $x^{-0.88}$ for an infinite linear source.

In order to predict absolute concentration values under a wide range of meteorological conditions, formulas (3) and (4) are not always satisfactory, mainly due to the difficulty of determining the coefficients C and the uncertainty in the choice of parameter n based on wind speed profile measurements. However, they are very useful for predicting the scattering and spreading of aerosol clouds, as well as for analyzing experimental data on the behavior of such clouds under different atmospheric conditions.

Calder's theory, in the case of diffusion under adiabatic conditions, leads to the approximate formulas:

$$\chi_\tau = \frac{Q \cdot \tilde{u} \cdot exp\left[-\frac{\tilde{u}}{k \cdot u_* \cdot x}\left(\frac{y}{a} + z\right)\right]}{2 \cdot k^2 \cdot a \cdot u_*^2 \cdot x^2} \quad (5)$$

$$\chi_l = \frac{Q}{k \cdot u_* \cdot x} \cdot exp\left(-\frac{\tilde{u} \cdot z}{k \cdot u_* \cdot x}\right) \quad (6)$$

where:
k – von Kármán constant,
a – the ratio of the transverse and vertical turbulence degree,
$u_* = (\tau_0/\rho)^{1/2}$,
τ_0 – wind friction stress on the Earth's surface,
ρ – air density.

Using these equations, the concentration of smoke from a point or linear source located at ground level can be expressed in terms of easily measurable meteorological values, namely: the ratio, a, which can be determined from wind gust records, and the friction velocity, u_*, which can be calculated from the wind profile.

These data are only applicable under conditions of small temperature gradients (cloudiness, moderate or strong wind). Increased gradients lead to rapid scattering, especially vertically, whereas the transition from a positive gradient to a negative one (inversion) significantly decreases the diffusion rate.

Consequently, during welding of gas pipelines, aerosol smoke is mixed with air due to transverse and longitudinal dispersion, convective transfer, and molecular diffusion. When the wind is calm, only molecular diffusion affects the distribution of the aerosol cloud.

The results of aerosol dispersion modeling during manual arc welding of hydrocarbon pipelines provide a more detailed understanding of the spatial and temporal distribution of hazardous substances in the welder's breathing zone. These outcomes serve as a basis for: justifying the use of effective individual and collective protective measures; defining safe exposure durations for personnel involved in welding operations; improving the design of ventilation systems during both construction and maintenance phases; and formulating recommendations for updating occupational safety regulations related to welding activities.

Conclusion

1. Welding of gas pipelines under repair and construction is carried out both in semi-open spaces (underground pipelines) and in open areas (above-ground gas pipelines). In both cases, manual electric welding is primarily used, which is characterized by a significant impact of harmful substances on the human body, as the distance from the welding site to the welder is only 20–30 cm.
2. Empirical dependencies have been established to determine the concentrations of aerosols, gaseous substances, and the pollution index of welders' workplaces, which is important for forecasting the influence of harmful substances on workers during the construction and operation of gas pipelines.
3. Mathematical models of aerosol distribution have been developed. It has been substantiated that the main physical processes involved are diffusion combined with heat transfer influenced by convective airflows. Based on a modified version of Sutton's mathematical model, it has been shown that during welding of above-ground pipelines in laminar wind conditions, aerosol fumes mix with the air solely due to molecular diffusion, while in underground welding, aerosol spreading is determined by the physical processes involved in welding torch formation.
4. The modeling results provide a foundation for: substantiating effective individual and collective protective measures; determining safe exposure durations for personnel in welding environments; optimizing the design of ventilation system during both construction and maintenance phases; and developing recommendations for revising occupational safety regulations related to welding processes.

To ensure the robustness of the results, experimental validation under real-world conditions is required and is planned as the next phase of the study. Subsequent research will also aim to present tailored safety guidelines derived from the modeling outcomes and to assess their advantages over conventional welder protection strategies.

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