Investigation of the processes of separation and spread of welding aerosols taking into account various types of heat and mass transfer to ensure safe welding conditions in confined space

*Yuriy I. Bulygin**, *Dmitriy V. Rogozin*, *Irina S. Kuptsova*, *Natalia N. Azimova*, and *Viktor F. Khlystunov*

Don State Technical University, 344000 Rostov-on-Don, Russia

Abstract. Russia has a well-developed network of pipeline transport. Its installation and repair is carried out using arc welding. Typically, arc welding is associated with harmful sprays of aerosols, especially in cases where flux cored wires are used for welding. Given the difficult weather conditions in the pipeline construction area, the use of shelters (booths, tents) is considered as an obligatory requirement for the conditions of welding on the installation. The work is aimed at theoretical substantiation of methods for controlling excessive pollution of the environment with welding aerosols and gases in confined spaces, which will allow creating technologies for designing systems and means of dust and heat protection for welders working in the installation conditions.

1 Relevance

The urgency of the work lies in the development of domestic technologies to ensure safe working conditions for welders, including building and repairing main pipelines. In the production of such work, the welder is often in so-called confined conditions and even in confined spaces (airtight cabins) where traditional types of ventilation cannot be used. In this case, a rapid increase in the content of harmful substances occurs, which is also exacerbated by increased thermal irradiation, an increase in the temperature of the medium, and the inconvenient position of the welder's body. The intensity of separation of the welding aerosol in the gas and solid phases is due to the dissociation of chemical components that react at high temperatures. During dispersion, fine particles of toxic fine dust and gas contamination of space are formed. The systematic influence of welding aerosol, gases in the conditions of the heating microclimate, as well as the lack of the necessary means of protection for welders, causes the growth of occupational lung diseases as well as the central nervous system.

* Corresponding author: bulyur_rostov@mail.ru

2 Scientific importance of the issue

The classical model of a continuous medium on the basis of the Navier-Stokes equations adapts to the solution of the complex heat exchange problem with complex moving boundary conditions, which, unlike existing models of production hazards, takes into account not only the turbulence of gas-air flows, but also various types of heat exchange with a source of pollution and heat release. The mathematical model is applicable to various objects, takes into account the technological parameters of the welding process and the expanded spectrum of harmful substances released into the working area, which allows to determine not only the concentrations of harmful substances, but also the parameters of the industrial microclimate in the work area of semi-closed confined spaces with natural and forced ventilation. As a result of full-scale and numerical experiments, dependencies are obtained and factors determining the formation of the air mobility fields, temperature, relative humidity and concentration in the air of the semiclosed confined spaces and objects studied are determined, which will allow them to classify and develop recommendations for the safe conduct of welding operations.

Scientific novelty consists of the following provisions:

- Chemical composition of the gaseous and solid constituent of the welding aerosol released during welding by flux-cored wire Innershield NR-207 and the specific values of the release of harmful substances that are necessary for the generation of initial data for the subsequent modeling of heat and mass transfer.
- The non-stationary three-dimensional k - ε model of turbulence, which describes the processes of separation and spread of the welding aerosol, taking into account the different types of heat exchange for determining the parameters of the air quality condition of the welding booths.
- Methodology for calculating the required air exchange for ventilating the welding cabin on the main pipelines, taking into account the technological parameters of the welding process for the flux-cored wire and the extended spectrum of harmful substances released into the working area.
- Determination of the influence factors of the technological parameters of the welding process of the Innershield NR-207 flux cored wire on the intensity of emission of harmful substances.
- The project of a mixed ventilation system for a welding booth used in the construction of main pipelines.

3 Short review of literature

The need for mathematical modeling in the study of the processes of the distribution of harmful substances and heat, in conditions of active ventilation of premises was noted in the works of Elterman VM, Titov VP, Kuvshinova Yu.Ya., Grititlina MI, Polushkina VI, Minko VA, Kokorina O.Ya., Poza M.Ya., Logacheva I.N., Logacheva K.I., Talieva VN, Datsyuka TA, Polosina I.I. and others. [1-8]. In these papers, various approaches to constructing mathematical models of ventilation processes are considered, which are based on the equations: motion, continuity of the medium, thermal conductivity and matter transfer. Mathematical modeling of the processes of heat and mass transfer of harmful substances and excess heat in the premises is associated with the consideration of three-dimensional objects with complex geometry, distributed systems of supply and discharge of air through ventilation openings, placed equipment of complex shape and sources of harmful substances. Earlier, the authors considered a non-stationary three-dimensional mathematical model of heat and mass transfer of harmful impurities and heat in an industrial environment with active ventilation and sources of pollution and heat generation,

which allows for the inclusion of swirling gas-air flows. The standard k-epsilon turbulence model, adapted for welding workshops equipped with stationary work stations with pollution sources, took into account only the convective component of heat exchange, which is justifiable for large rooms (with a low density of distribution of pollution sources), especially since the results of model calculations with Only the convective component was well correlated with the experimental data obtained. However, for the purposes of this study, when we are dealing with small confined spaces where it is necessary to take into account heated bodies up to a high temperature (when welding) adjacent to each other as additional heat sources, it is no longer possible to neglect radiation heat transfer.

At the present time, a large number of different models for the calculation of turbulent currents have been created: Boussinesq, Spalart-Almarasa, the method of large eddies, the Reynolds stress model, the k-epsilon and the k-omega model and a number of others. They differ from each other in the complexity of the solution and the accuracy of the flow description. Since direct calculation of the complete Navier-Stokes equations [9] for a three-dimensional turbulent flow requires considerable computational resources, all the main models used are based on certain approximations. In addition, there is a difficulty in numerical methods of solving, which involves the need to use extremely small grids in calculating the flow in a turbulent boundary layer, which leads to a violation of the stability of the calculation.

As a result of the review and analysis of existing models, it is possible to use the k-epsilon model of turbulence, which is most often used in solving practical problems and giving quite satisfactory results for determining the fields of concentrations of harmful substances and parameters of the production microclimate in the conditions of air stream swirls and taking into account the convective and radiation constituent of heat exchange for the calculation of ventilation processes and processes of the spread of harmful substances (HE) and excess heat (IT). To implement the mathematical model, the most preferred are the SolidWorks or ANSYS software.

On the other hand, the development of the ventilation system for the welding cabin is based on the calculations of the required air exchange for the design of its ventilation, which must take into account the technological parameters of the welding process of the flux-cored wire and the extended spectrum of harmful substances released into the working zone (their toxicity). However, the data bank on specific parameters of explosive emissions in welding with flux cored wire Innershield NR-207 is practically absent and needs experimental clarification. In addition, to compare and classify the electrodes for the toxicity of the CAs that are formed, the summation effect must be taken into account, the International Welding Institute proposed to use the toxicity index CA [10,11], which is the intensity of air exchange (IV in m³ / h) taking into account the toxicity of its components, rather than the leading toxic component.

Thus, taking into account the most toxic of all the chemical components of the substance and the effect of summation of the harmful effects of harmful substances released during the welding with flux cored wire will make it possible in the calculation to avoid errors in determining the required air exchange and choosing the power of the power plant of the cab ventilation system. Thus, the required air quality in the welder's working area (RZ) can be achieved and safe working conditions for welders in terms of the chemical factor and microclimate parameters are ensured.

4 Formulation of the problem

It is experimentally to investigate the different types of heat transfer under conditions of limited confined space during welding and the behavior of a mathematical model describing the contribution of various heat exchange components, including radiation, that

affect the formation of concentration, temperature, air mobility and heat stress fields in the medium under study. The authors developed an experimental setup and selected equipment for the purpose of studying the processes of diffusion of heat in a fluid, accounting for heat transfer in solids and radiant heat transfer. For this purpose, a model object was selected and assembled in the form of a vented cube with a simple geometric shape with a source of heat released inside and the ability to create airflow in it (a discharge pipe with an integrated fan is made). The numerical solution of the problem is carried out in the CAD-CAE package of Solid Works, for this purpose a technique was developed for constructing in the software environment of the SAE package a model of a ventilated cube with sources of heat dissipation of various capacities. Simulated full-scale experiments for a cubic body (the welder's cabin model) and their modeling with the help of the developed approaches, comparison of the results of measurements of airflow rates and temperatures with the calculated data showed qualitative and quantitative coincidence of the process parameters, which is an indicator of the adequacy of the heat and mass transfer model.

A software is proposed that allows calculating the fields of concentrations of harmful substances, temperatures, air movement and heat stresses for hermetic cabins on main pipelines where the welder works in confined conditions. Questions of convergence of calculations and choice of a finite element mesh are investigated. With the help of the software used, it is possible to carry out calculations that will allow designing the general exchange and local supply and exhaust ventilation of the sealed cabin, and to select the ventilation equipment based on the estimated pressure loss and throughput. The choice of local ventilation capacity is based on determining the pressure loss, the amount of gas released, the excess heat of the mixture, the departure of the umbrella. An exhaust hood for local ventilation is equipped with a flexible air duct, which allows rapid movement in the welding zone.

In the future, on the basis of numerical calculations and experimental studies, specific engineering solutions will be developed that will allow the user to design a protection system for a welder operator for a sealed cabin used in the construction of main pipelines.

5 Mathematical model of heat and mass transfer of impurities in relation to constrained welding conditions, taking into account various types of heat transfer

The basic equations (1-3) describing the processes of interaction of ventilation flows with convective currents from pollution sources are: the equation of continuity (conservation of mass), momentum and energy (heat) transfer:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0; \quad (1)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) + \frac{\partial p}{\partial x_i} = \frac{\partial}{\partial x_j} (\tau_{ij} + \tau_{ij}^R) + S_i; \quad i=1,2,3. \quad (2)$$

$$\frac{\partial (\rho H)}{\partial t} + \frac{\partial (\rho u_i H)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(u_j (\tau_{ij} + \tau_{ij}^R) + q_i \right) + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho \cdot \varepsilon + S_i u_i + Q_H; \quad (3)$$

$$q_i = \left(\frac{\mu}{Pr} + \frac{\mu_t}{\sigma_c} \right) \cdot \frac{\partial h}{\partial x_i}, \quad i=1,2,3. \quad (4)$$

$$H = h + \frac{u^2}{2}; \quad (5)$$

where u – flow rate, ρ – density, p – medium pressure, H – specific energy, $S_i = -\rho \cdot g_i$ – gravitational component; h – enthalpy, Q_H – volumetric intensity of heat source; τ_{ij} – tensor of viscous stresses; q_i – change in heat; ε – The rate of dissipation of turbulent kinetic energy; constant $\sigma_c = 0,9$, Pr – Prandtl number; μ – coefficient of dynamic viscosity, μ_t – turbulent dynamic viscosity coefficient.

To determine the fields of concentrations of the components of the mixture in the air, the equation of convective-diffusion transport of matter (6) is solved, which is given below:

$$\frac{\partial(\rho y_m)}{\partial t} + \frac{\partial(\rho u_i y_m)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[(D_{mn} + D_{mn}^t) \frac{\partial y_m}{\partial x_i} \right] + S_m, m=1,2,...,M \quad (6)$$

where D_{mn}, D_{mn}^t molecular and turbulent diffusion matrices m component into n environment, S_m – intensity of selection into n environment m component of matter. In

accordance with Fick's law on diffusion: $D_{mn} = D \cdot \delta_{mn}$, $D_{mn}^t = \delta_{mn} \cdot \frac{\mu_t}{\sigma}$. Between the concentrations of the components of matter, the following algebraic relation holds: $\sum_m y_m = 1$. The transfer of the kinetic energy of turbulence and the rate of dissipation of

turbulent energy are taken into account by two additional equations.

With the Lewis number $Le=1$ the diffusion and thermal conduction equations become identical and the profiles of excess concentrations and temperatures turn out to be similar. Model equations describe both laminar and turbulent flows and are solved for certain initial and boundary conditions using the finite element numerical method in the SolidWorks Flow Simulations environment. Heat transfer in solid bodies and radiation heat transfer:

$$\frac{\partial(\rho e)}{\partial t} = \frac{\partial}{\partial x_i} \left(\lambda \frac{\partial T}{\partial x_i} \right) + Q_H; \quad (7)$$

where $e = cT$, c — specific heat, T — temperature, λ — thermal conductivity, Q_H — Specific (per unit volume) heat release of the heat source. The heat emitted from a surface unit is defined as:

$$Q_R = \varepsilon \cdot \sigma_0 \cdot T_w^4 \quad (8)$$

where ε — degree of blackness of the surface, σ_0 — the degree of blackness of the surface is the Stefan-Boltzmann constant, T_w — surface temperature.

6 The object of research on the example of semi-closed spaces and design schemes

Figure 1 shows the object of the study, where work is carried out with acetylene-oxygen welding or gas cutting of reinforcement in the manufacture of reinforcing mesh and

frameworks in the conditions of a construction site in an open area in a square pit at a depth of 1.5 m with a total volume of 24 m³ (pit volume in model calculations changed to 48m³ at constant depth). Welding works are performed directly by a welder with the assistance of an assistant observer. The determining factor of the effect on the gas content and air condition in the pit is the wind. In model calculations, we changed the values of the air mobility from 1m / s to 10 m / s, besides, a change in its direction was observed.

Fig. 1. The object of the study with geometric dimensions and plotted with a basic mesh.

Fig. 2. Design schemes that take into account the direction of the wind.

Figure 2 shows the calculation schemes for recording the movement of air in the presence of wind. Formation of indicators of the state of working conditions of the welder occurs under the influence of aerodynamic processes occurring in pits under the influence of wind.

7 Calculations of gas content and air mobility in pits using protective screens

Having determined the direction and speed of the wind, as well as the parameters (power) and the type of welding, it is possible to recommend not only optimal locations (workplaces) for the welder and his assistant, but also to develop requirements for the rational arrangement of protective screens and their sizes (Fig.3).

Fig.3. Cutoff of the NOx concentration field in the wind at the back 1 m / s, with the protective screen installed: a) - in the front (leeward side); b) behind (windward side).* scale "mass concentration" shows the ratio of the mass fraction of substances. To obtain a "concentration", the obtained value must be multiplied by the density of the medium. The indicated interval in the translation for "concentration" corresponds to the interval (0-2.5 · 10-5 kg / m3), which in the translation for MPC NOx corresponds to (0-5 MPC).

The results of model calculations prove that the most favorable position of the welder is the recommended position with his back to the wind movement from the windward side (wind behind). It can be seen from Figure 3 that the installation of a protective screen from the windward side with the same location of the welder relative to the wind significantly reduces the concentration of harmful substances in the work area. The vertical section of the nitrogen oxide concentration fields in the pit shows that it reaches the sanitary and hygienic norm of the MPC in the welder's breathing zone.

8 Calculations of gas content and air mobility in pits using mobile ventilation units

As follows from the results of the calculation (Fig. 4a), when PVA is used with a fan capacity of $L = 500 \text{ m}^3 / \text{h}$, the gas component of the welding aerosol in the form of nitrogen oxide is not completely captured and some of the gases in the presence of wind can get into the welder's breathing zone.

Fig.4. Vertical sections of the fields of NOx concentrations in windless weather, with the installation of PVA of different performance outside the pit.

This situation is illustrated by Fig. 4a, which shows the direction of the gaseous nitrogen oxide inside the pit, indicating the vortex currents of air that arise inside during welding operations. Once the performance of the fan has been achieved, complete recovery of the off-gases is achieved. This was demonstrated to be increased to $L = 1200 \text{ m}^3 / \text{h}$, with a suction distance from the welding location (approximately 0.4 m), in Fig. 4b, which shows a heat-resistant suction hose coming from a fan that is installed outside the pit. In practice, PVA with a variable capacity is used, in order to achieve optimal ventilation parameters, depending on the welding regime (emission of harmful gases and excess heat, as well as gas contamination and microclimate in the well). In cases where the welder has to tilt directly above the place of separation of welding gases and vapors, the installation site of the hood should be justified so that no harmful gases pass through the breathing zone. The suction spot is organized directly at the welding site, but on the side of the welder's face at a distance of 0.2-0.4 m.

9 Expected results of scientific research and their scientific and applied significance

As a result of ongoing experimental and theoretical studies, the following will be obtained:

1. Data bank on the composition and welding-technological properties of self-shielded flux cored wires Innershield.
2. Scientific-based requirements for the creation of regulatory and technical documentation for the safe conduct of welding operations in the installation of oil and gas pipelines.
3. Analytical dependencies of the chemical composition of the weld metal weld seams made with powdered wire Innershield NR 207, 208, as a function of welding parameters; the calculated dependences of the mechanical properties of welded joints as a function of the chemical composition of the weld.
4. Chemical composition of the welding aerosol released during welding with flux cored wire Innershield NR-207, 208.
5. Analytical dependencies of thermal effects of chemical reactions and physical processes of substantiation of gas and solid aerosol constituents, expressed through thermodynamic statistically.
6. Engineering nomograms for the rapid determination of the values of gross and specific emissions of harmful substances during welding (surfacing) with powdered wires Innershield NR-207, 208 based on the laws of chemical kinetics for thermal or energy conditions of welding (surfacing).
7. Scientifically grounded ways of optimization of sanitary-and-hygienic parameters for powder wires Innershield NR-207, 208.
8. Nonstationary three-dimensional mathematical model of the processes of separation and distribution of welding aerosol taking into account various types of heat exchange, which is realized in modern productive software. [12].
9. Spatial model of temperature fields in the air of the working area of a sealed welding cabin with indications of critical pressures and concentrations of harmful substances in the operator's breathing zone (welder).
10. Scientific-grounded principles of design and use of a mixed ventilation system (combination of local and general exchange elements) in a closed space of a welding cabin, taking into account spatial temperature fields and concentration of harmful substances.

10 Conclusions

The presented model calculations of the fields of concentrations, air mobility and temperatures in the semi-enclosed pit space can be performed for the investigated enclosed spaces by the example of welding booths for the construction and installation of gas-pipe lines. The described model allows not only to clarify the calculated zones of gas contamination and microclimate parameters of workplaces of welders in cramped conditions, but also to determine the directions of measures to reduce the levels of exposure of hazardous and harmful factors to workers.

References

1. M.I. Grititlin, O.N. Timofeeva, E.N. Elterman, L.S. Eljanov, *Ventilation and heating of shipyards* (Sudostroenie, Leningrad, 1978)
2. M. Ia. Pos, ABOK Magazine, 1, 8 (1990)
3. M.Ia. Pos, R.D. Katz, A.I. Kudryavtsev, *Calculation of airflow parameters in ventilated rooms based on "gluing" currents. Air distribution in ventilated buildings*, 26-51 (Moscow, 1984)
4. G.M. Pozin, Izv. vuzov. Stroitel'stvo i arkhitektura, 11, 122 (1980)
5. V.I. Polushkin, *Fundamentals of aerodynamics of air distribution in ventilation and air conditioning systems* **135** (Leningrad State University, Leningrad, 1978)
6. A.V. Portyannikov, *Modeling of air exchange of industrial premises with local exhaust and general ventilation*, Diss. kand. techn. science (Voronezh, 2010)
7. V.P. Titov, ABOK Magazine, 3/4, 16 (1992)
8. A.A. Busnaina, Technical solutions through technical cooperation, 2, 130 (1991)
9. V.I. Polejaev, A.V. Bune, N.A. Verezub, *Mathematical modeling of heat and mass transfer based on the Navier-Stokes equations* (Nauka, Moscow, 1987)
10. E.J. Magnusson, C.H. Rosendahl, Studies of the possibilities of classifying welding electrodes according to fume generation, II-923-80 Conf Paper (1980)
11. K.B. Migai, O.N. Timofeeva, E.I. Yushtin, *Safety during electric welding in shipbuilding* (Shipbuilding, Leningrad, 1964)
12. Y.I. Bulygin, D.A. Koronchik, A.N. Legkonogikh, M.G. Zharkova, N.N. Azimova, IOP Conference Series: Earth and Environmental Science, **66**, 1, 012015 (2017)