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AIR EXCHANGE DYNAMICS IN ELECTRICAL PREMISES OF CHEMICAL INDUSTRIES

The mathematical model of dynamics of explosive substances concentrations in premises with air overpressure is considered. Dependences of concentration of explosive substances in air stream subject to the thickness of walls are obtained. The parameter describing interaction of external air and premise air on wall (partition) internal border is identified.

Introduction

According to normative documents [1], [2], electrical premises situated on the area of chemical industries should have guarantee air overpressure to prevent explosives and dust entry inside these premises. Air overpressure is provided by forced ventilation combined with building measures. As a rule, heating of these premises is combined with ventilation.

Harmful explosives can find their way to the premises with air overpressure both with incoming air and through pores, cracks, and openings in the walls.

Average explosives concentration in premises with air overpressure

$$C = \frac{G_n}{V},$$
(1)

where C is the explosives concentration in premise, mg/m^3; G_n is the total amount of harmful explosives in premise, мг; V is the volume of premise, m^3.

Explosives concentrations in premise will change by dC because of emission of harmful explosives with incoming air and in disorganized way. The total amount of harmful explosives is equal to

$$dG_n = V \cdot dC. \tag{2}$$

The change in total amount of harmful explosives in premise, caused by emission of harmful explosives with incoming air, is equal to

$$dG_{np} = (C - C_{np}) \, V_{np} \cdot d\tau, \tag{3}$$

where C_{np} is the harmful explosives concentration in incoming air, mg/m^3; V_{np} is the discharge of incoming air, m^3/h.

The change in total amount of harmful explosives in premise, caused by emission of harmful explosives with incoming air, is equal to

$$dG_{н} = (C - C_{н}) \, V_{н} \cdot d\tau, \tag{4}$$

where $C_{н}$ is the concentration of harmful explosives, entering a premise in disorganized way, mg/m^3; $V_{н}$ is the discharge of the air being removed from a premise in disorganized way through walls, m^3/h.

The total amount of harmful explosives will change by

$$dG_n = -VdC = [CV_{np} - C_{np}V_{np} + CV_{н} - C_{н}V_{н}] \, d\tau = [C \, (V_{np} + V_{н}) - C_{np}V_{np} - C_{н}V_{н}] \, d\tau, \tag{5}$$

$$-VdC = [C \, (V_{np} + V_{н}) - C_{np}V_{np} - C_{н}V_{н}] \, d\tau. \tag{6}$$

The minus sign in the left member of equation indicates that что concentration of harmful explosives in a premise will reduce with time, because this is the purpose of ventilation. Let us integrate

$$ln \left[\frac{C(V_{\bullet п} + V_{,}) - C_{\bullet п}}{V_{\bullet п} + CV_{,}} \right] \Bigg|_{C_{\tau=0}}^{C} = - \frac{\tau(V_{\bullet п} + V_{,})}{V} \Bigg|_{\tau=0}^{\tau}, \tag{7}$$

we obtain $\quad C = C_{\tau=0} \exp\left\{ -\frac{V_{\bullet п} + V_{,}}{V} \tau \right\} + \frac{C_{\bullet п}V_{\bullet п} + CV_{,}}{V_{\bullet п} + V_{,}} \left\{ 1 - \exp\left[-\frac{V_{\bullet п} + V_{,}}{V} \tau \right] \right\},$

$$\int_{C_{\tau=0}}^{C} \frac{-VdC}{C(V_{\bullet п} + V_{,}) - C_{\bullet п}V_{\bullet п} + CV_{,}} = \int_{\tau}^{0} d\tau \, .$$

Rate of air circulation:

- for incoming air
$$n = \frac{V_{\cdot np}}{V} ; \tag{9}$$

- for exfiltration air
$$n_{эк} = \frac{V_H}{V} ; \tag{10}$$

then
$$C = C_{\tau=0} \exp\left\{-(n + n_{эћ})\tau\right\} + \frac{C_{\cdot p}V_{\cdot p} + CV_{,}}{V_{\cdot p} + V_{,}} \left\{1 - \exp\left[-(n + n_{эћ})\tau\right]\right\}. \tag{11}$$

In stationary conditions, when $\tau \to \infty$,

$$C = \frac{C_{\cdot p}V_{\cdot p} + CV_{,}}{V_{\cdot p} + V_{,}}. \tag{12}$$

With $\tau = 0$
$$C = C_{\tau = 0.} \tag{13}$$

With $C_{np} = 0$, that is with rather clean incoming air

$$C = C_{\tau=0} \exp\left\{-(n + n_{эћ})\tau\right\} + \frac{CV_{,}}{V_{\cdot p} + V_{,}} \left\{1 - \exp\left[-(n + n_{эћ})\tau\right]\right\}, \tag{14}$$

in stationary conditions
$$C_{\tau \to \infty} = \frac{CV_{,}}{V_{\cdot p} + V_{,}}. \tag{15}$$

If initial concentration of harmful explosives is equal to 0, then

$$C = \frac{C_{\cdot p}V_{\cdot p} + CV_{,}}{V_{\cdot p} + V_{,}} \times \left\{1 - \exp\left[-(n + n_{эћ})\tau\right]\right\}, \tag{16}$$

in stationary conditions
$$C_{\tau \to \infty} = \frac{C_{\cdot p}V_{\cdot p} + CV_{,}}{V_{\cdot p} + V_{,}}. \tag{17}$$

It follows from the dependences (11), (14), (16), that if in premises with air overpressure concentrations of harmful explosives are more than concentrations of harmful explosives in incoming air or concentrations of harmful explosives, entering a premise in disorganized way, then, the growth of concentrations of harmful explosives in premises with air overpressure does not occur.

If concentrations of harmful explosives inside of premise with air overpressure will be less than concentrations of incoming harmful explosives, than the growth of concentrations in these premises will occur until these concentrations in premise are more, than concentrations of incoming harmful explosives.

Concentrations of incoming harmful explosives at industrial areas of chemical enterprises, generated as a result of extreme natural conditions (calm, mist, precipitation), volley emissions and escapes, may be several times more than maximum permissible ones, lower explosive limit [3]. As the results of full-scale tests show, large difference in concentrations of outdoor and indoor air in premises with pores, slots, leakages in the walls (partitions) is the reason for harmful substance ingress in premise with air overpressure.

As it was notices above, air exchange in chemical industries is performed as follows: incoming air (ΣG_n) is fanned into premise with the help forced mechanical ventilation system and is removed through pores, slots, leakages ($\Sigma G_в$) in the walls (partitions) in disorganized way, in this case the following condition should be met:

$$\Sigma G_n - \Sigma G_в > 0. \tag{18}$$

Let's determine which concentrations occur in outward-directed air flow that is towards to к harmful substances source (industrial area or chemical enterprise workshop). Let's discuss the case of plane-parallel flow (Fig.).
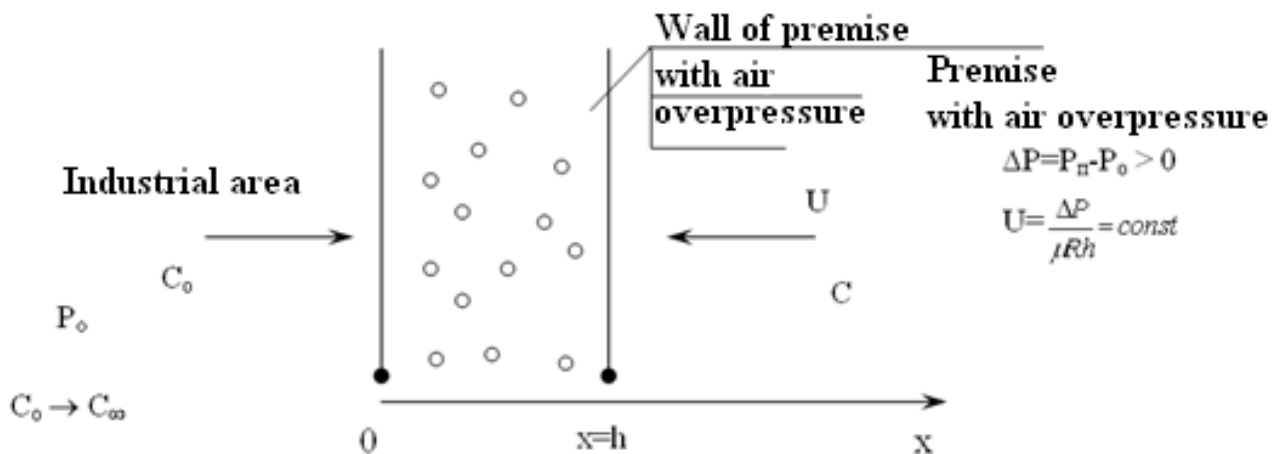

Fig. The scheme for determination of explosives concentration
in counter plane-parallel flow in walls (partitions)

Suppose that in zero cross-sections (see Fig.) noxious gas-air admixture is equal to C_0. In this case concentrations in the sections at the distance of x directed towards to the flow can be determined from the system of differential equations

$$\begin{cases} \varepsilon \dfrac{\partial C_1}{\partial \tau} = D \dfrac{\partial^2 C_1}{\partial x^2} + U \dfrac{\partial C_1}{\partial x}, & 0 \leq x \leq h, \ \tau > 0, \tag{19} \\[2mm] \dfrac{\partial C_2}{\partial \tau} = D_n \dfrac{\partial^2 C_2}{\partial x^2} + U \dfrac{\partial C_2}{\partial x}, & h \leq x < \infty, \tau > 0, \tag{20} \end{cases}$$

where C_1, C_2 are the concentrations of noxious gas-air admixture, mg/m^3; U is the flow velocity, m/sec (direction opposite to axe X is taken for positive one); D, D_n are exchange factor in partition and in premise, respectively, m^2/sec (under laminar flow this is the molecular diffusion coefficient, under turbulent flow this is the turbulent diffusion coefficient); ε is the porosity of partition (wall), $0 \leq \varepsilon \leq 1$; τ is the time, sec.

The equation (19) is the diffusion equation in filter partition subject to convective transport. To solve differential equations (19), let us substitute independent variable

$$\xi = x + \frac{U}{\varepsilon}t, \ t=t_1, \ C_1(x,t) \rightarrow C_1(\xi,t_1);$$
(21)

$$\frac{\partial C_1}{\partial t} = \frac{\partial C_1}{\partial t_1} + \frac{\partial C_1}{\partial \xi}\frac{\partial \xi}{\partial t_1} = \frac{\partial C_1}{\partial t_1} + \frac{U}{\varepsilon}\frac{\partial C_1}{\partial \xi};$$
(22)

$$\frac{\partial C_1}{\partial x} = \frac{\partial C_1}{\partial \xi}, \ \frac{\partial^2 C_1}{\partial x^2} = \frac{\partial^2 C_1}{\partial \xi^2};$$
(23)

$$\varepsilon\frac{\partial C_1}{\partial t_1} + U\frac{\partial C_1}{\partial \xi} = D\frac{\partial^2 C_1}{\partial \xi^2} + U\frac{\partial C_1}{\partial \xi};$$
(24)

$$\frac{\partial C_1}{\partial t_1} = \frac{D}{\varepsilon}\frac{\partial^2 C_1}{\partial \xi^2}.$$
(25)

Let us denote relation $\frac{D}{\varepsilon} = a^2$ in equation (25), we obtain $\frac{\partial C_1}{\partial t_1} = a^2\frac{\partial^2 C_1}{\partial \xi^2}.$ (26)

Fundamental solution of the equation (25) is probability (error) integral

$$\Phi(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-\alpha^2}d\alpha,$$
(27)

where

$$z = \frac{\xi}{2\sqrt{a^2 t}} = \frac{x + \frac{U}{\varepsilon}t}{2\sqrt{\frac{D}{\varepsilon}t}}.$$
(28)

$$\Phi(-z) = -\Phi(z); \ \Phi(\infty)=1.$$
(29)

The solution of the equation (28) under initial conditions

$$C_1(x,0) = \begin{cases} C_0 \ \text{при} \ x<0, \\ 0 \ \ \text{при} \ x>0; \end{cases} \begin{pmatrix} \varepsilon = const \\ D = const \end{pmatrix}$$
(30)

takes the form $\qquad\qquad C_1(x, t) = A + B\Phi(z).$ $\qquad\qquad$ (31)

Substituting initial conditions (30) in equation (31), we obtain

$$\begin{cases} C_0 = C_1(x,0) = A + e\Phi(-\infty) = A - e, \ \text{x}<0; \\ 0 = C_1(x,0) = A + e\Phi(\infty) = A + e, \ \text{x}>0. \end{cases} \qquad (32)$$

It follows that $A = \dfrac{1}{2}C_0$, $B = -\dfrac{1}{2}C_0$.

Thus, the solution of (19) under initial conditions (30) is the function

$$C_1(x, t) = \frac{1}{2}C_0[1 - \Phi(z)], \qquad (33)$$

where $0 < x < h$, $0 < t < \infty$; h is the thickness of porous partition (wall), m;

or $\qquad$ $$C_1(x,t) = \frac{1}{2}C_0\left[1 - \Phi\left(\frac{x + \dfrac{U}{\varepsilon}t}{2\sqrt{\dfrac{D}{\varepsilon}t}}\right)\right] = \mu(t) \ . \qquad (34)$$

With $x = h$ and under initial conditions

$$C_1(h, t) = \mu(t) \qquad (35)$$

the solution of the equation (19) is the function

$$C_1(h,t) = \frac{1}{2}C_0\left[1 - \Phi\left(\frac{h + \dfrac{U}{\varepsilon}t}{2\sqrt{\dfrac{D}{\varepsilon}t}}\right)\right] = \mu(t) \ . \qquad (36)$$

Dependences (33), (34), (36) indicate that field of concentrations is formed in air flow through partition opposite to its movement. Thus, overpressure is required, but it is inadequate to prevent penetration of explosives from industrial areas under bad weather conditions and escapes.

In the field $x \geq h$, when $\Delta P = P_n - P_n = 0$, i. e. $U = 0$, the equation (20) takes the form

$$\frac{\partial C_2}{\partial \tau} = D_{\Pi}\frac{\partial^2 C_2}{\partial x^2} . \qquad (37)$$

Under boundary condition (35), i. e.

$$C_2(h, t) = \mu(t) \qquad (38)$$

and restricted $C_2(\infty, t)$, the solution of equation (37) cam be written as follows

$$C_2(x,t) = \frac{C_0 D_{\varPi}}{2\sqrt{\pi}} \times \int_0^t \frac{x-h}{D_{\varPi}(t-\tau)^{3/2}} \cdot e^{-\left[\frac{(x-h)^2}{4D_{\varPi}\cdot(t-\tau)}\right]} \cdot \mu(\tau)d\tau \ . \tag{39}$$

Under stationary conditions equations (19) and (20) take the form

$$\begin{cases} D\dfrac{\partial^2 C_1}{\partial x^2} + U\dfrac{\partial C_1}{\partial x} = 0, & (40) \\[4mm] D_n\dfrac{\partial^2 C_2}{\partial x^2} + U\dfrac{\partial C_2}{\partial x} = 0, & (41) \end{cases}$$

The solution of differential equations (40), (41) has the form (with $D = const$, $D_n = const$)

$$C = C_3 + C_4 \cdot e^{\lambda x}, \tag{42}$$

where C_3, C_4 are the constants of integration.

Substituting expression (43) into equation (41), we obtain

$$\frac{\partial C_1}{\partial x} = C_4\lambda e^{\lambda x}; \ \frac{\partial^2 C_1}{\partial x^2} = C_4\lambda^2 e^{\lambda x}, \tag{43}$$

$$DC_4\lambda^2 e^{\lambda x} + UC_4\lambda e^{\lambda x} = 0, \ \ D\lambda + U = 0, \ \lambda = -\frac{U}{D}; \tag{44}$$

similarly, substituting expression (43) into equation (44), we obtain

$$\lambda = -\frac{U}{D.} \ . \tag{45}$$

Having solved differential equations (40) and (41), we obtain

$$C_1 = C_3 + C_4 \cdot e^{-\frac{U}{D}x}, \tag{46}$$

$$C_2 = C'_3 + C'_4 \cdot e^{-\frac{U}{D.}x} \ . \tag{47}$$

Constants of integration can be found from boundary conditions ($\varepsilon = 1$):

$$\begin{cases} x = 0, \ C_1 = C_0; \\ x = h, \ C = C_1 = C_2; \\ x = \infty, \ C_2 = 0; \end{cases} \tag{48}$$

where C_0 is the concentration of a explosive in industrial area (see Fig.), mg/m^3; h is the actual thickness of partition, m; C is the concentration of explosive substance at the boundary of a wall and a premise, mg/m^3;

$$C_3 + C_4 = C_0, \tag{49}$$

$$C_3 + C_4 \cdot e^{-\frac{U}{D}h} = C'_3 + C'_4 \cdot e^{-\frac{U}{D.}h}, \tag{50}$$

$$C'_3 = 0, \tag{51}$$

$$\frac{\partial C_1}{\partial x}\Big|x = h_- = \frac{\partial C_2}{\partial x}\Big|x = h_+, \tag{52}$$

It can be found from equations (46) and (47) that

$$\frac{\partial C_1}{\partial x} = -C_4 \frac{U}{D} e^{-\frac{U}{D}x}, \tag{53}$$

$$\frac{\partial C_2}{\partial x} = -C'_4 \frac{U}{D} e^{-\frac{U}{D_{II}}x}, \tag{54}$$

substituting obtained expression into equation (52), we obtain

with $x = h$ $\qquad C_4 \frac{U}{D} e^{-\frac{U}{D}h} = C'_4 \frac{U}{D} e^{-\frac{U}{D_{II}}h}, \quad C'_2 e^{-\frac{U}{D.}h} = C_2 \frac{D.}{D} e^{-\frac{U}{D}h}, \tag{55}$

substituting equation (55) into (50), we obtain

$$C_3 + C_4 \cdot e^{-\frac{U}{D}h} = C_4 \cdot \frac{D.}{D} e^{-\frac{U}{D.}h},$$

$$C_3 = C_4 \cdot e^{-\frac{U}{D}h}\left(\frac{D.}{D} - 1\right); \tag{56}$$

substituting expression (56) for C_3 into equation (49), we obtain

$$C_4 \cdot e^{-\frac{U}{D}h}\left(\frac{D.}{D} - 1\right) + C_4 = C_0, \quad C_4 = \frac{C_0}{1 + \left(\frac{D.}{D} - 1\right)Hb^{-\frac{U}{D}h}}. \tag{57}$$

Thus, for boundary conditions (48) with $D = $ const, $D_n = $ const, $\varepsilon = 1$, simultaneous solution of equations (49) and (50) gives dependence

$$C = C_1 = C_2 = C_4 \cdot e^{-\frac{U}{D}h}\left(\frac{D.}{D} - 1\right) + C_4 \cdot e^{-\frac{U}{D}x}. \tag{58}$$

With $x = h$, equation (58) takes the form

$$C(h) = C_4 e^{-\frac{U}{D}h} \frac{D_n}{D} = \frac{C_0 \frac{D_n}{D} e^{-\frac{U}{D}h}}{1 + \left(\frac{D_n}{D} - 1\right) e^{-\frac{U}{D}h}}. \tag{59}$$

Equation (58) can be modified as follows:

$$C = C_4 \left(e^{-\frac{U}{D}h} \left(\frac{D_n}{D} - 1\right) + e^{-\frac{U}{D}x} \right), \tag{60}$$

substituting C_4 from (57) into equation (60), we obtain

$$C = \frac{C_0 \left(e^{-\frac{U}{D}h} \left(\frac{D_{II}}{D} - 1\right) + e^{-\frac{U}{D}x} \right)}{1 + \left(\frac{D_{II}}{D} - 1\right) e^{-\frac{U}{D}h}}, \tag{61}$$

let us denote

$$\frac{D_{II}}{D} - 1 = d, \tag{62}$$

then, equation (61) takes the form

$$C = \frac{C_0 \left(d e^{-\frac{U}{D}h} + e^{-\frac{U}{D}x} \right)}{1 + d e^{-\frac{U}{D}h}}. \tag{63}$$

Dependences (58), (60), (63) indicate that field of concentrations is formed in air flow opposite to its movement. Thus, there is an opinion that it is sufficient to provide over-pressure to prevent explosives and dust penetration into a premise. It is wrong opinion.

Let us consider d in formula (62). This index defines interaction of outdoor air and premise air at the internal boundary of a wall (partition), therefore, it can be identified as outdoor and indoor air interaction index.

Exchange factor can be determined as

$$D = 0.25 \, \bar{\varepsilon}^{1/3} L^{4/3}, \tag{64}$$

where $\bar{\varepsilon}$ is the quantity of kinetic energy, decaying in a unit of time in a unit of mass, m^2/sec^3; L is the linear dimension describing the volume, where exchange process is investigated, m.

Substituting expression (64) into equation (62), we obtain

$$d = \frac{0.25\bar{\varepsilon}_n^{-1/3} L^{4/3}}{0.25\bar{\varepsilon}^{-1/3} h^{4/3}} - 1 = \frac{\bar{\varepsilon}_n^{-1/3} L^{4/3}}{\bar{\varepsilon}^{-1/3} h^{4/3}} - 1, \qquad (65)$$

where $\bar{\varepsilon}_n$ is the energy of inflow streams of premise, related to a unit of mass of premise air and to a unit of time, m^2/sec^3; $\bar{\varepsilon}$ is the energy of air flow in pores and in openings of a wall, related to a unit of air mass, passed through a wall, and to a unit of time, m^2/sec^3.

Formulae (61), (63) show that the longer distance x/h from a source, the less concentration of harmful substances. If distance x (the length of partition or wall channel) is very small, then even at high velocities of air flow it is impossible to reduce concentration in premise with overpressure.

Let us determine what concentrations of explosives should be in industrial if they are equal to maximum permissible ones at the boundary of a wall and a premise. For this purpose we rearrange the formula (63) as follows:

$$C_o = \frac{C(1 + de^{-\frac{U}{D}h})}{de^{-\frac{U}{D}h} + e^{-\frac{U}{D}x}}. \qquad (66)$$

Conclusion

It has been shown (see, for example, equation (66)) that fields of explosives concentrations arise at the internal boundary of a wall in a premise with air overpressure when explosives concentrations in industrial area are higher than maximum permissible ones. These fields of explosives concentrations can lead to emergency situation.

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