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AIR DISTRIBUTION IN LARGE VOLUME VENTILATION OBJECTS

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ABSTRACT
Main task of ventilation is to ensure safety environment for people and equipment via pollutants' liberation and distribution control. Processes of emissions and distribution by air currents in ventilation objects with one directional flow are well studied and controlled though they are problem in ventilation objects with large volumes. In such objects different aero-dynamical zones exist. This paper comments parameters of ventilation objects with large volumes and presents main expressions, describing pollutants and air flows distribution.

INTRODUCTION

Directed flows of air currents in ventilation systems assumes well controlled ventilation paths with clearly defined aero-dynamical characteristics. Majority of mine workings can be described as the above-mentioned objects. There exists though suck configurations, object to ventilation, where ventilation current is not clearly defined, zones with free and semi-restricted jets, stagnation and recirculation ones can be obeserved.

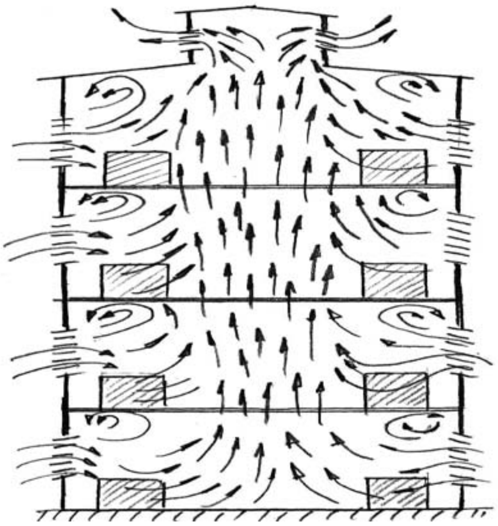

Figure 1. Industrial plant

Similar ventilation configurations are many of industrial ventilation objects [2] – industrial plants and halls, with different in type, action and consistence heat and mass sources, surface facilities of underground mine, camera type and blind mine workings, metro stations, car parks etc. Classification of one object as Ventilation Object with Large Volume (VOLV) assumes definition of critical relationships between dimensions, ventilation in and out flows, aero-dynamical characteristics, and similarity criteria.

One possible approach for analysis of air flows distribution is physical and mathematical modelling, which include:

- Based on analysis of technological processes clarification of all potential sources;
- Description of sources and their influence;
- Modelling of their distribution;
- Zones description where safety conditions are violated;
- Planning of ventilation measures;
- Modelling of their influence;
- Results analysis.

This paper deals with part of these problems, namely – mathematical expressions, presenting main processes in ventilation objects with large volumes.

VENTILATION OBJECTS WITH LARGE VOLUMES

As already mentioned in the introduction, ventilation object with uniform flow modes in different zones and directions of ventilated volume are analysed in this paper. Figures 1, 2 and 5 present such objects. Depending on purpose of different sections of objects, controllable, uncontrollable and isolated zones can be defined (figure 3). From other side, in regard to way of air inflow and distribution zones with free and semi-restricted jets, main air current, stagnantion and recirculation zones exist.

These general determinations for analysed types of objects depend on geometrical, aero-dynamical and ventilation characteristics. Objects' dimensions are presented by length (L), width (B) and height (H), as well as inflow/outflow holes, serving as supply and exhaust air paths. One example of industrial plant with large volume is represented by& main hall with length 180 m; width - 45 m; height – 20.95 m (15.50 to the roof and 17.30 to фонара).

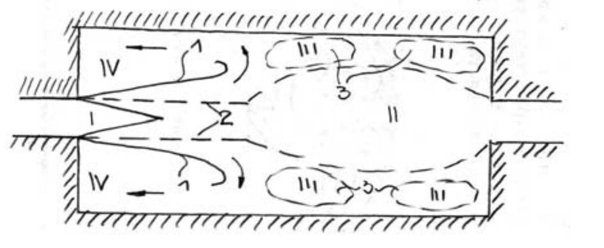

Figure 2. Camera type mine working

The roof is with фонар, having windows along the whole hall length. Plant volume is 137 214 m^3, which assignes it as VOLV. Inflow/outflow supply/exhaust openings are located at levels 0.00, 4.50, 10.30 and 17.30. Their surfaces (not all of the open able) are approximately 2000 m^2. One impeding factor is existence of great holes at level 4.50 with whole surface 716 m^2. They create local circulation currents, which prevent proper distribution of available air.

Other VOLV class are camera type mine workings. Their dimensions vary in ranges 150 x 10 x 7 m. Suppply/ecxaust oppenings are also variable. For this types of objects are valid following relationships [7]:

- If air supply working height equals to the chamber height, while its width is incomparable small to its width then flat free jet is formed in the camera.
- If height and width of air supply working are incomparable in dimensions with corresponding camera dimensions then round free jet or very similar to it is formed.

Initial configuration of ventilated areas can be done based on the following expressions:

- *Short premises*: Fresh air is reflects in the opposite wall. Beyond the jet zone re-circulation zone is composed, where fresh and exhaust air is mixed. Supply air is more than exhaust one. In order to ventilate one premises by directed through one supply place flow, its length should comply with the expression:

$L \leq 0,62\, k_1 \sqrt{B\, H}$, where:

k_1 – air jet disintegration coefficient,

$$\frac{u_{\max}}{u_0} = k_1 \frac{\sqrt{A_0}}{x}$$

u_{max} – maximal outflow velocity of ventilation tag, m/s;
u_o – average velocity of air jet, m/s;
A_o – area of jet inflow, m^2;
x – distance from inflow location, m

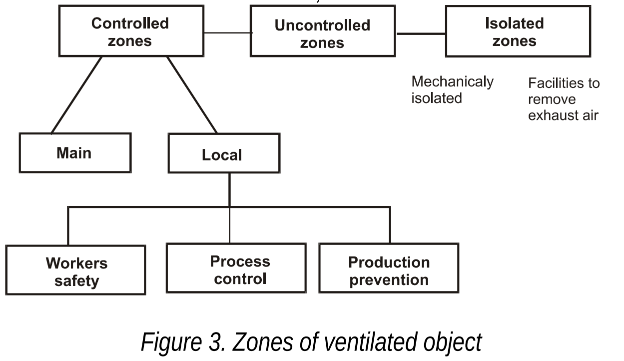

Figure 3. Zones of ventilated object

- *Long premises*: if $L > 0,62\, k_1 \sqrt{BH}$. Inflowing fresh air jet disintegrates and reversed flows become dominated. Critical length, for which jet is shortened, is defined ($x_{\max} > L_{крит}$). According to Norwegian researchers [4] $x_{\max} \approx 3,3\sqrt{BH}$.
- *Wide premises*: In order to ventilated one premises through fresh air, inflowing from one hole, the following expression should be valid: $B \leq 3H$. If $B > 3H$ premises is classified as long one.

MODELLING OF POLLUTANTS' LIBERATION AND DISTRIBUTION

Pollutant sources according to the place of their liberation are classified as:

- external;
- internal;
- linked with ventilation system.

Outside air is normally less polluted, compared with the exhaust air out flowing from ventilated object unless due to mistake in ventilation the exhaust air become a supply one. Sources, associated with ventilation system usually are as a result either of improper operation or bad project.

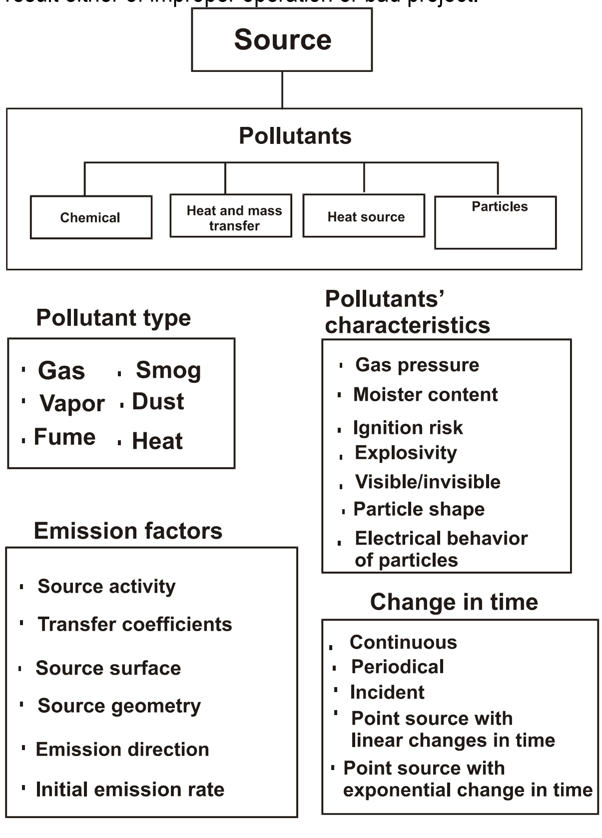

Figure 4. Source characteristics

Internal sources can be:

- chemical (particles, gas, aerosols, vapors, smog);
- biological (bacteria, viruses);
- physical – heat parameters (temperature, velocity, moisture) leading to human discomfort beyond normal parameters and causing radiation, noise, vibrations and other negative phenomena.

Figure 4 shows main parameters, defining processes of pollutants' formation, liberation and distribution. Modeling and analysis of distribution should take into account all interacting factors and to give proofs for neglection and/or inclusion into model one or other phenometa, depending on the actual problem examined. Polution type and its behavior in time are parameters, which are defined approximately well. Specific attention should be paid to emission rate. Some expressions for its evaluation are given below:

Process with clear pollutant formation parameters

$M = R_1 * T_{process}$

where:

M – total emission rate, kg/h;

R_1 –t liberated amount of gas, fume or vapor, kg/min;

$T_{process}$ – average time duration for pollutant liberation within one hour, min/h;

Pressure differences inside/outside the pipeline

$$M = k\,C\,V\sqrt{\frac{m}{T}} \tag{1}$$

where:

к – coefficient $k \in (1 \div 2)$;

C – coefficient depending on pressure, given in the table below:

Pressure, atm	<2	2	7	17	41
Coefficient C	0,121	0,166	0,182	0,189	0,192

V – inside pipeline diameter, m^3;

m – molecular weight of gas/vapors

T – temperature in the pipeline, °C

Gas emissions from open spaces (reservoir, spots on the floor)

Nuselt, Prandl and Grashov criteria numbers are applied:

$$Nu = \frac{u\,d}{D}; \quad \Pr = \frac{\nu}{D}; \quad Gr = \frac{u d^3(\rho_0 - \rho_1)}{\nu^2 \rho_1}$$

where:

d – typical dimension, m;

u – liberation velocity from the taken surface,m/s;

D – diffusion coefficient, m^2/s;

ν - kinematic viscosity, m^2/s;

ρ_o – density of air environment, kg/m^3;

ρ_1 – density of air environment, closed to evaporating surface, kg/m^3;

- *Emission rate under laminar flow mode* $(2.10^2 < Gr\Pr < 2{,}3.10^8)$

$$M = F.A.d^{-1/4} D^{1/2} (C_1 - C_0)^{5/4} \left|(M_{air}/M_l - 1)\right|^{1/4} \text{ g/s} \tag{2}$$

where:

$$F = \begin{cases} 0{,}334 \ when\ M_{air} > M_l \\ 0{,}184 \ when\ M_{air} < M_l \\ 0{,}224 \ for\ wet\ vertical\ surfaces \end{cases}$$

A – evaporating surface, m^2;

M_{air} – relative molecular weight of air;

M_l - – relative molecular weight of evaporating substance

- *Emission rate under turbulent flow mode*

$$M = F.A.D^{1/3} (C_1 - C_0)^{4/3} \left|(M_{air}/M_l - 1)\right|^{1/3} \text{ , g/s} \tag{3}$$

where:

$$F = \begin{cases} 150 \ when\ M_{air} > M_l \\ 75 \ when\ M_{air} < M_l \\ 113 \ for\, wet\, vertidcal\, surfaces \end{cases}$$

Evaporation rate:

$$M = 7.4(a + 0.017V)(P_2 - P_1)101.3\frac{A}{P_B} \tag{4}$$

where: M is evaporation rate $[kg/h]$

V – air velocity across the surface, $[m/s]$

a - coefficient reflecting the influence of air movement, given in [4]

P_2 - saturated vapours pressure over the liquid, кPa

P_1 - water vapour pressure above the surface, кPa

A – evaporation surface, m^2

P_B - barometric pressure, кPa.

Gas, vapours and dust particles are distributed in air space due to convection flows of ventilation and turbulent and molecular diffusion. Main equation, which presents process of pollutant with concentration C_A distribution, is convection diffusion equation:

$$\frac{\partial C_A}{\partial t} + u_x\frac{\partial C_A}{\partial x} + u_y\frac{\partial C_A}{\partial y} + u_z\frac{\partial C_A}{\partial z} = D_{AB}\left(\frac{\partial^2 C_A}{\partial x^2} + \frac{\partial^2 C_A}{\partial y^2}\frac{\partial^2 C_A}{\partial z^2}\right) + q_c \tag{5}$$

Initial and boundary conditions are given in table 1. They should be particularly specified according to concrete problem.

One simplified expression for concentration C_x evaluation at distance x from the source:

$$C_x = C_0\, e^{-\frac{u}{D}x} \tag{6}$$

where:

Co – source concentration, mg/m^3;

u – air velocity, m/s;

x – distance from source, m;

D – diffusion coefficient, m^2/s.

Value of D depends on air flow velocity and on the way of it inflowing and distribution into the premises. In incoming zone (the jet has not been disintegrated) it is calculated under well known formula [Taylor, Laigna etc.]. Outside this zone the following formula should be applied [4]:

$$D = c\,\varepsilon^{\frac{1}{3}}\ell^{\frac{4}{3}} \text{ , m}^2\text{/s} \tag{7}$$

where:

c = 0,25 ± Δ - coefficient under reliability interval Δ;

$$\ell = \begin{cases} premisses\, height \\ ventilation\ instalation\ diameter \end{cases}$$

$\varepsilon = \dfrac{E_{prem}}{M\,\tau}$ kinetic energy, lost in air mass M[kg] for time τ [s].

$$E_{prem.} = \sum E_{jets} + \sum E_{conv.} + \sum E_{movingobjects}$$

$$E_{jets} = \frac{1}{2}\rho\, V u^2$$

$E_{conv} = \dfrac{g\,W_{conv.}\,H}{1{,}8\,c_p\,T_0}$, $W_{conv.}$ – heat source convection component

$$E_{movingobjects} = \frac{1}{2} k A u^2 \rho\, t$$

Table 1. Boundary conditions

Boundary condition	Flows values	Scalars
Fresh air inflow	Air volume, velocity, pressure	T(temperature), C_i (concentration of impurity i); Turbulence degree
Exhaust air	Air volume, velocity, pressure	Т(температура), C_i (концентрация на вредност i);
Large holes	$P_{\text{пълно}}$	T(temperature), C_i (concentration of impurity i); Turbulence degree of inflowing air into zone
Walls	$\vec{v} = 0$ outside heat	T (temperature),
Pollution sources	S_c – pollutant emission Heat flow	

AIR DISTRIBUTION MODELLING

In ventilation objects with great volumes in respect to air flows behaviour following types of zones exist:

- Main air flow;
- Free or semi-restricted jets, generated by air supply equipments;
- Re-circulation zonesрециркулационни зони;
- Stand still zones.

Mathematical modelling [5,3] can help in zone evaluation and definition as well as transition between modes – fully turbulent, transitional, laminar. Classical model in mechanics, presenting turbulent air flow, consists of mass and momentum conservation (Navie-Stocks):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_1)}{\partial x_1} + \frac{\partial(\rho u_2)}{\partial x_2} + \frac{\partial(\rho u_3)}{\partial x_3} = 0 \qquad (8,9)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j u_i) = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \overline{u_i u_j}\right] + \rho\beta\delta_{i2}\left(T - T_{ref}\right)$$

where: $\vec{u} = u(x_1, x_2, x_3; t)$

$\rho = \rho(x_1, x_2, x_3; t)$

Indexes i and j are used, instead of traditional x,y,z in order to transfer easily mathematical model into its numerical analogue.

Simplified turbulent model can be applied, namely:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j u_i) = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho\beta\delta_{i2}\left(T - T_{ref}\right) \qquad (10)$$

Most widely applied turbulent models to solve Navie-Stocks equations are $k-\varepsilon$ and $k-\omega$. Turbulent viscosity is presented in the way:

$\mu_t = C_\mu\, \rho \dfrac{k^2}{\varepsilon}$ for $k-\varepsilon$ model and $\mu_t = C_\mu\, \rho \dfrac{k}{\omega}$ for $k-\omega$ model.

Turbulent model application is obligatory due to the need to model different turbulent modes [1,4] and also transition from one mode in another. $k-\varepsilon$ model can create numerical problems in zones with weak turbulence. The reason is that when $k \to 0$ expression $\dfrac{\varepsilon^2}{k}$ representing turbulent diffusion in ε equation tent to infinity. ε equation is:

$$\frac{\partial}{\partial x_j}(\rho u_j \varepsilon) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\left(\frac{\partial \varepsilon}{\partial x_j}\right)\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1} P_k - C_{\varepsilon 2}\rho\varepsilon) \qquad (11)$$

Such kind of problem doesn't exist in $k-\omega$ model:

$$\frac{\partial}{\partial x_j}(\rho u_j \omega) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varpi})\left(\frac{\partial \omega}{\partial x_j}\right)\right] + \frac{\omega}{k}(C_{\varpi 1} P_k - C_{\varpi 2}\rho\omega)$$

In zones with weak turbulence diffusion term tent to 0 and no numerical problems cause. Special attention in airflows distribution in large volumes should be paid to air jets. They predefine ventilation measures effectiveness and ventilation strategy [1].

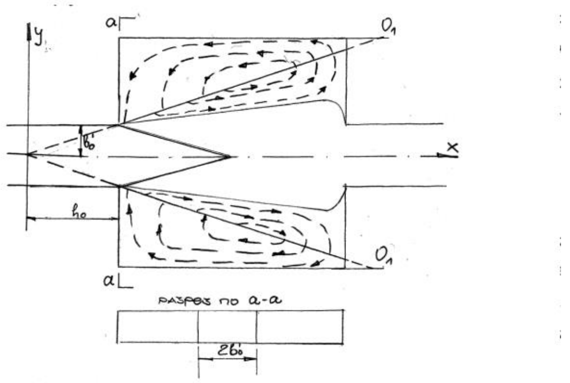

Figure 5. Free jet elements

Air jets are formed as a result of directed air inflow through ventilation devices. In case no influence of walls, ceilings and other jets exist, the jet can be considered as a free jet. Very often its identity depends on reverse flows and other currents in ventilated space with different temperature, which lead to origination and action of Archimedes forces. Free jets are classified according to ventilation outlet to: compact, linear, radial, swirling. Four zones are observed in jet development and existence (figure 5)

- Zone 1 (jet kernel) – short zone $(2 \div 6d)$. Centerline velocity remains nearly equal to supply velocity;
- Zone 2 (transition zone) – Depend on diffuser type. For a compact jets it is from 8 to 10d. Maximal velocity may vary inversely with the square root of the distance from the outlet;

- Zone 3 (fully established turbulence). Its length depends on the air jet shape, type and size of supply diffuser, initial velocity, turbulence characteristics of ambient air. It has major engineering importance since this is the place where jet enters the occupied region;
- Zone 4 (terminal/decay zone) or the place where jet looses its identity.

Expressions below can be used to evaluate jet velocity in arbitrary place in jet. Diffuser type is assumed rectangular with dimensions 2L x 2B. In point with coordinates x,y,z against jet center, velocity is defined under the following expression:

$$u(x,y,z)=\frac{u_0}{2}\sqrt{\left(erf\,\frac{L-y}{cx}+erf\,\frac{L+y}{cx}\right)\left(erf\,\frac{B-z}{cx}+erf\,\frac{B+z}{cx}\right)} \quad (12)$$

Centerline velocity (y=0, z=0) is:

$$u(x)=u_0\sqrt{erf\,\frac{L}{cx}+erf\,\frac{B}{cx}} \quad (13)$$

Above expressions are valid for zones 1 to 3.

In case diffusion type is rectangular with great length ($L\to\infty$) and width 2B (linear diffuser) velocity is evaluated under the expression:

$$u(x,y,z)=\frac{u_0}{2}\sqrt{erf\,\frac{B-z}{cx}+erf\,\frac{B+z}{cx}} \quad (14)$$

while on the centerline it is:

$$u(x)=u_0\sqrt{erf\,\frac{B}{cx}} \quad (15)$$

Centerline velocity for radial diffuser type is [4]:

$$\frac{u(x)}{u_0}=1-\exp\left(-\frac{d^2}{4c^2x^2}\right) \quad (16)$$

Known expressions for flows formation in large volume premises [7] are given below:

- In case Re number, related to free jet initial outlet area is in range 1900-2500, only turbulent jet is formed in the premises, initiated from outlet diffuser;
- In case Re number is less than 1900 only laminar or laminar-turbulent jets can be presented in the premises, last of them forming when Re ≅ 1800.

CONCLUSION

Air flows and pollutant distribution can be made by applying the following approaches:

- Experimental measurements and calculations;
- Mathematical and computer modeling;
- Combination of the above.

Mathematical and computer modeling include:

- Mathematical and physical model description (equations, expressions, coefficients);
- Equations' transitions into computer model;
- Numerical solution of discrete model.

Mathematical and computer modeling [3,6] shortened the path for investigation of a given problems to practical results. This approach is extremely useful in the following cases:

- Lack of data and possibility for real measurements;
- Complex problem – in our case different in number and structure interrelated zones;
- Known initial and boundary conditions – supply and exhaust air volumes;
- Need to optimize ventilation parameters in order to choose more effective scheme for ventilation.

Additional advantage of simulation approaches is that it can give hints where and what to measure so as to obtain close to reality model thus leading to realistic models' results.

Mathematical models (general and simplified), presented in this paper will serve as a basis for velocity field evaluation and furthermore – to important fro ventilation point of view zones in ventilated premises.

More accurately definition of models' parameters, experiments on models' adequacy, applicable mathematical models to transform into discrete analogue, the results themselves are the object of following works. .

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