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THE UTILIZATION OF VORTEX EFFECT FOR VENTILATION AND HEATING OF INDUSTRIAL PREMISES

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Some Soviet and foreign authors note advantageous features of whirling air currents contributing to the intensification of on-going processes and shortening their duration. The features are as follows: increased turbulence levels, higher values of diffusion coefficient, heat- and mass-exchange rate, etc. For this reason the utilization of whirling air currents in room ventilation and heating might prove of high efficiency.

W. Janiszewski (Poland) has recommended that ventilation be arranged in such a way as the clean air be supplied tangentially (along the room outline) while the foul air be removed via a device placed in the vertical axis of air flow whirling.

Such an arrangement of air supply and removal has been approved of by B. Berounský(Chechoslovakia).

In the USSR, vortex currents have been studied by V.V. Stepanov with a view to normalizing workplace atmosphere in open-cast mining facilities. The whirling air movement was achieved by way of air being supplied using two parallel fans, producing opposite-directed air streams. The author thus obtained a number of analytical relationships describing the alteration of air flow parameters across the main area of unobstructed propagation of artificial eddy current.

The Skočinskij Mining Institue (USSR) studied the effects of air flow circulation around a horizontal roadway axis on the expansion of suction area. This study findings as well as the investigation of tangential air supply in boiler furnaces and generation of spinning air flows in short and long pipes showed the aerodynamic pattern of whirling air flows to be affected by the spinner (outlet), chamber (room) and air remover (exhaust) dimensions.

The multiplicity of factors affecting flow formation and three-dimensionality of velocity field has hampered the generalization of study findings and discouraged mathematical process modelling. All the experiments used to be performed for concrete study conditions with no respect for the specific nature of air currents in real-life ventilated work premises and are hence not advised to be used directly for the arrangement of ventilation of modern industrial premises, which normally present as a relatively confined space, accommodating large-size heat- and gas-emitting equipment and workposts of those attending to it. This latter fact determines the strict requirements to the characteristics (temperature, velocity, toxic contaminant load, etc) of the whole of the whirling current.

With a view to finding out the applicability of vortex air currents to room ventilation and developing an engineering method of system calculation, we, in the Soviet National Research Institute for Occupational Safety and Health (VCNIIOT), undertook a special experimental study using a method of physical modelling of processes and mathematical methods of experiment planning.

While attempting to build up a vortex air current for the purposes of room ventilation, one shall bear in mind the principal peculiarities of an air flow circling above a fixed foundation (floor), when a secondary, radial current forms in the vicinity of the foundation, inwardly directed towards the whirling axis. Due to the continuity of air motion, an ascending current evolves up and along the vertical axis, which, in discussed circumstances, should be utilized to its full capacity for the removal of toxic contaminants out of human environment.

The study assumed that the dominant influences were a so called twist parameter, expressing the following relationship:

(1) $\Sigma\bar{F}_{in}=F_{in}/F_r$,

where ΣF_{in} is the total area of outlet openings for the supply of incoming air and F_r is room floor area, and relative height of the ventilated space:

(2) $\bar{H}=H/R$,

where H is the room height and R is the radius of vortex to be arranged.

It seemed relevant for the solution of the assumed problem to determine the effects of the supply outlet location above the floor level:

(3) $\bar{h}_{o.l.}=h_{o.l.}/H$.

It was shown that air removal device (exhaust) location

(4) $\bar{h}_{ex.l.}=h_{ex.l.}/H$

produced no significant effects. Nor did their dimensions:

(5) $\bar{F}_{ex.}=F_{ex.}/F_{in}$.

We also studied the effects of the manufacturing equipment crowdedness, overall dimensions and levels of heat emission (in terms of heat amount) upon workplace microclimate conditions.

The study helped determine the conditions for a steady vortex current development and proposed equations for minimum supplied air energy values sufficient for its formation.

The aerodynamic investigations ascertained the self-similarity of vortex air current as related to the **Re** number, derived from the velocity of air flow coming in via supply outlets, while air temperature distribution studies confirmed the validity of using the formulae extrapolating the model microclimate parameters to real-life conditions and obtained on tne basis of the equality of the Archimedes test both for field and model conditions

Up to now we have failed to find any literary data on noxa distributions about the cross-sectional area of whirling currents. Due to the existence of the radial velocity component during air current whirling over a rough fixed surface, no impurities were detected over 30% of the cross-sectional area in the external zone, 68% had emission levels below current exposure limits, while just about 2% of the area, situated in the whirling axis, displayed emission levels 1.5 times those prescribed by the existing standards. These findings were obtained under conditions when the air was supplied via two slot outlets of the same height as the test room's and placed in the opposite corners, while the outgoing air was removed through an aperture in the middle of the cover (ceiling) and tracer gas supplied across the whole of the perforated floor area.

The experimental study task was to obtain mathematical equations, relating vortex ventilation efficiency parameters to the factors affecting it, and establish optimum ventilation system characteristics.

By way of exemplification see below some equations for the calculation of:
- air exchange efficiency coefficient

(6) $K=(t_{w.z.}-t_{in})/(t_{out}-t_{in})$,

where $t_{w.z.}$, t_{in} and t_{out} are working zone, incoming and outgoing air temperature values, respectively.

(7) $K=0.28-0.02\ X_2-0.03\ X_4+0.02\ X_5-0.03\ X_1X_4+0.03\ X_1X_5+$
$+0.06\ X_2X_3-0.03\ X_2X_5$;

- relative maximum air flow velocity in working zone

(8) $\bar{V}^{max}_{w.z.}=V^{max}_{w.z.}/V_{in}=0.051+0.01\ X_1-0.017\ X_2+0.004\ X_1X_5-$
$-0.004\ X_2X_3$,

where X_1, X_2, X_3, X_4, X_5 are code values of variables, equal to:

(9) $X_1=(h_{o.l.}/H-0.28)/0.09$;

(10) $X_2=(h_{o.l.}/H-0.19)/0.19$;

(11) $X_3=(h_{ex.l.}/H-0.69)/0.31$;

(12) $X_4=(R_{a.e.}\cdot m^{0.5}-61.2)/31.3$;

(13) $X_5=(q\cdot m^{0.5}-104)/52$,

where $R_{a.e.}$ is air exchange rate.

m values shall be derived from the following table as a function of the ventilated space dimensions.

Parameter name	Ventilated space dimensions (m)			
	12x12x(6÷8)	18x18x(9÷12)	24x24x(12÷16)	36x36x(18÷24)
m	10	15	20	30

Using the obtained equations we plotted isolines for K and $V^{max}_{w.z.}$ (room $q=23.6 J/m^3s$).

With the help of the resulting chart one may choose an optimum location for the distribution and exhaust devices.

The difference between the maximum and minimum values of working zone temperature can be checked by the formula presented:

(14) $\Delta t_{w.z.}=1.47-0.2\ X_2+0.37\ X_5$.

The $\Delta t_{w.z.}$ values should not exceed the ones established by special regulations.

Using the relationship, reflecting the effects of various influencing factors on the fluctuations of air exchange rate values, one can determine a total air exchange rate required for the assimilation of excess heat L^h_{in} and dilution of toxic gases down to the existing MAC values L^g_{in}:

(15) $L^h_{in}=K\dfrac{Q}{(t_{out}-t_{in})\gamma c_p}$ (m^3/s);

(16) $L^g_{in}=K\dfrac{G\cdot 10^6}{MAC}$ (m^3/s),

where Q and G are excess heat (J/m^3s) and gas emission level (mg/s).

Variation of K (at $q=23.6 J/m^3s$) between 0.2 and 0.36 indicates a significant reduction in air exchange rate, by a factor of 2-6, normally required in common ventilation methods (in the case when manufacturing equipment is evenly distributed about the whole of the shopfloor area vortex ventilation proves less efficient, air exchange rate being reduced only by 20-30%).

The VCNIIOT studied the efficiency of vortex ventilation, employed in the air heating mode, on an industrial building simulator (model). Air vortex movement was achieved through use of special outlets, discharging flat and compact jets. Heat- and gas-emitting equipment mock-ups were installed inside the building model, either evenly distributed about the floor area or focused in the centre.

When designing an air heating system one is supposed to determine the incoming air temperature t_{in} (°C) at a given air flow rate, sufficient for the dilution of contaminants down to MAC - L^{g}_{in} (m^3/hr) and amount of heat, required to make up for heat losses:

(17) $Q_{in}=(Q_{rhl}-Q_{eq})$ (W/h),

where Q_{rhl} is room heat losses and Q_{eq} - equipment heat emissions.

To assess an air heating system's hygienic efficiency one needs to know the excess temperature values of working zone air:
- minimum value

(18) $\Delta t^{min}_{w.z.}=t^{min}_{w.z.}-t_{in}$ (°C);

- maximum value

(19) $\Delta t^{max}_{w.z.}=t^{max}_{w.z.}-t_{in}$ (°C),

including a resulting maximum temperature gradient across the working zone area

(20) $\Delta t_{w.z.}=t^{max}_{w.z.}-t^{min}_{w.z.}$

and maximum workplace air flow velocity - $V^{max}_{w.z.}$.

The following initial data, required for the calculation and design of room air ventilation by air vortex current, can be drawn from a ventilation system design project:

- geometrical room dimensions AxBxH (m);
- geometrical equipment dimensions F_{eq} (m^2), h_{eq} (m) and its location (concentrated in the centre or distributed across the floor area), type of harmful emissions (heat, gas) and their rate G (kg/h);
- outlet opening area F_{in} (m^2), their location above the floor level h^{o}_{1} (m) and air outflow velocity V_{in} (m/s) (the air removal device being mounted on the ceiling);
- minimum allowable workplace air flow temperature and velocity values for cold and transitional periods are prescribed by standards and other relevant regulations.

Incoming air temperature and parameters of air in human-occupied zones shall be determined as follows:

- the values of maximum relative working zone temperature gradient

(21) $\Delta\bar{t}_{w.z.}=(t^{max}_{w.z.}-t^{min}_{w.z.})/(t_{in}-t_{out})$

shall be calculated using one of the formulae from Table 1, while those of minimum relative gradient

(22) $\Delta\bar{t}^{min}_{w.z.}=(t^{min}_{w.z.}-t_{out})/(t_{in}-t_{out})$

- by one of the Table 2 formulae.

Tables 1 and 2 contain formulae to be used for the calculation of air heating parameters when the air is supplied in flat jets.

Table 1. Equations for determining $\Delta\bar{t}_{w.z.}$

Harmful emission sources situated around the centre of the floor	$0.218-0.029X_1+0.02X_2-0.014X_3-0.033X_1X_2+0.012X_2X_3+0.02X_2X_4+0.01X_3X_6+0.026X_4X_6-0.032X_4X_5-0.011X_3X_5+0.23X_3X_4$
Harmful emission sources distributed about the floor area	$0.277-0.042X_1+0.029X_2+0.024X_4+0.051X_5-0.031X_6-0.018X_4X_5-0.013X_3X_5$

Table 2. Equations for determining $\Delta\bar{t}^{min}_{w.z.}$

Harmful emission sources situated around the centre of the floor	$0.065-0.028X_1+0.34X_2-0.025X_3+0.015(X_5+X_1X_6)-0.052X_6+0.014X_1X_2-0.022(X_2X_4+X_4X_6)-0.014X_3X_6+0.016X_4X_5-0.027X_3X_4$
Harmful emission sources distributed about the floor area	$0.031-0.02(X_1+X_3)-0.034X_4-0.029X_5+0.03X_6-0.012X_2X_4-0.016X_4X_5+0.015X_3X_5$

First, a gradient is calculated between the incoming and outgoing temperatures for a given room heat deficit using the following formula:

(23) $\Delta t_{in}=t_{in}-t_{out}=(Q_{rhl}-Q_{eq})/c_p\cdot L^{g}_{in}\cdot\rho$

and next the values of $t^{max}_{w.z.}-t^{min}_{w.z.}$ (°C) and $\Delta t^{min}_{w.z.}$.

Based on the standard-stipulated values of $t^{min}_{w.z.}$ the incoming and outgoing air temperatures can be found by the following formulae:

(23) $t_{out}=t^{min}_{w.z.}-\Delta t^{min}_{w.z.}$ (°C)

(24) $t_{in}=t_{out}+\Delta t_{in}$ (°C).

Heat saving value is calculated by the following formula:

(25) $\Delta Q_{in}=c_p\cdot\rho\cdot L^g_{in}[(t^{min}_{w.z.})^{st}-t^{min}_{w.z.}]$

Hygienic evaluation of air heating arrangement is performed in the following way:

-relative excess temperatures of workplace air are calculated:

maximum $\Delta\bar{t}^{max}_{w.z.}$ - by a Table 3 formula;

mean $\Delta\bar{t}^{mean}_{w.z.}$ - by a Table 4 formula.

Table 3. Formulae for finding $\Delta\bar{t}^{max}_{w.z.}$

Harmful emission source in the centre of the floor	$0.284-0.056X_1+0.053X_2-0.039X_3+0.015X_5-0.06X_6-0.019X_1X_2+0.013X_1X_6-0.018X_4X_5$
Harmful emission sources spread about the floor area	$0.331-0.078X_1+0.048X_2-0.055X_3-0.034X_4-0.024X_6-0.033X_1X_2+0.025X_1X_6-0.028X_2X_3-0.03X_2X_4+0.034X_3X_6+0.026X_4X_6+0.018X_3X_5+0.014X_3X_4$

Table 4. Formulae for finding $\Delta t^{mean}_{w.z.}$

Harmful emission source in the centre of the floor	$0.16-0.014X_1+0.03X_2-0.047X_3-0.016X_4+0.031X_5-0.061X_6-0.008X_1X_2-0.009X_2X_4-0.018X_3X_4$
Harmful emission sources spread about the floor area	$0.141-0.025X_1+0.03X_3-0.021X_4+0.009X_6+0.01X_3X_6-0.01X_4X_5-0.011X_3X_4$

Next, absolute values of $\Delta t^{max}_{w.z.}$ and $\Delta t^{mean}_{w.z.}$ are found. Maximum workplace air flow velocity $V^{max}_{w.z.}$ is obtained using one of the Table 5 formulae, where

(26) $\bar{V}^{max}_{w.z.}=V^{max}_{w.z.}/V_{in}$.

Table 5. Formulae for determining $V_{w.z.}^{max}$

Harmful emission source in the centre of the floor	$0.18-0.018X_1+0.067X_2-0.025X_3-0.011X_4-0.011X_2X_3-0.005X_4X_5$
Harmful emission sources spread about the floor area	$0.117+0.052X_2-0.008X_3-0.02X_4+0.009X_6-0.009X_2X_4-0.01X_4X_6$

Table 6 reveals the essence of factors X_1, X_2, X_3, X_4, X_5 and X_6, which affect the efficiency of heating.

Table 6. Meaning and values of the main factors affecting heating efficiency

Factor name	Code designation	Fluctuation range
Relative height of outlet location above the floor level $\bar{h}_1^o=h_1^o/H$	$X_1=\frac{\bar{h}_1^o-0.275}{0.275}$	0-0.55
Relative outlet area for air outflow $\bar{F}_{in}=F_{in}/F_r$	$X_2=\frac{\bar{F}_{in}-0.0028}{0.0014}$	0.0014-0.0042
Relative room height $\bar{H}=H/\sqrt{F_r}$	$X_3=\frac{\bar{H}-0.375}{0.125}$	0.25-0.5
Relative equipment height $\bar{h}_{eq}=h_{eq}/h_{w.z.}$	$X_4=\frac{\bar{h}_{eq}-1.2}{0.4}$	0.8-1.6
Relative equipment-occupied area $\bar{F}_{eq}=\Sigma F_{eq}/F_r$	$X_5=\frac{\bar{F}_{eq}-0.245}{0.12}$	0.125-0.365
Specific heat emission by the equipment $q=Q_{eq}/V$ (W/m^3)	$X_6=\frac{0.91q\sqrt[4]{F_r}-78}{78}$	0-35.0

The authors have proposed engineering methods for the calculation and design of vortex ventilation and air heating, which are capable of determining workplace microclimate parameters and facilitating hygienic assessment of system performance.

SUMMARY

In order to find out the applicability of vortex air currents to room heating and ventilation, the Soviet National Research Institute for Occupational Safety and Health (Moscow) undertook a special experimental study using a method of physical modelling of processes and mathematical experiment planning methods. Engineering calculation methods were developed for the design of room heating and ventilation systems capable of producing optimum conditions for air supply, removal and consumption. The utilization of vortex effect helps bring down air flow rates (consumption) and amount of heat required to warm the room air.

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