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Impact of Air Distribution on Efficiency of Dust Capture from Metal Grinding —Bench Test Method

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Abstract: According to the Machinery Directive 2006/42/EC, one of the essential requirements relating to occupational safety and health hazards is to prevent dust pollution emitted by machinery during the implementation processes. Research on evaluation of emissions from machinery, according to the method of test bench using tracer gases, are currently being conducted in CIOP-PIB. This article presents some aspects of dust emission and efficiency of local exhaust ventilation (LEV) during metal grinding. Studies were performed with 10 sources of dust emissions during grinding. To evaluate the pollutants emission in the process of grinding metal products sulfur hexafluoride (SF_6) was selected as a tracer gas. The results show that wherever dust is emitted, the LEV should be supported by the general ventilation. Ensure good interaction between all elements of modifying the air flow and the spread of pollutants in the surroundings of the LEV is essential to effective protection of human working zone against pollutants. We used five variants of ventilation: ventilation turned off, the LEV, one-way general ventilation, mixed general ventilation and displacement general ventilation. An increase in the efficiency of dust capture depending on the source of emission by 2.5–14% was observed. This confirms that characteristics of flow resulting from the operation of ventilation is important in the spread of pollutants in the room.

Key words: Ventilation, Air distribution, Grinding, Machine, Emission, Bench test method, Tracer gas

Introduction

Undertaking the actions aimed at elimination of dust risk at source of its emission is required pursuant to the European Union Directives No. 2006/42/WE, 98/24/WE and 89/655/EWG implemented into the Polish law. The machines which create dust risk must be equipped with suitable collective protection equipment against dust[1]. According to the data of Main Statistical Office, the number of people employed in hazardous conditions of industrial dust in Poland was equal to 87.6 thousand in 2008, including approx. 52.9 thousand workers exposed to fibrosis inducing industrial dusts. Approximately 4.4 thousand people[2] were employed in carcinogenic dust risk conditions.

In all places exposed to dust emission it is recommended to partially or completely encase the sources of pollutants emission and, if it is not possible, the LEV is used, connected with dust separator or filtering device[3]. The role of the LEV is to capture the dust pollutants directly at the source of emission and protect against spreading in the working room. The choice of the LEV depends on both location of the source of emission as well as direction and velocity of dust pollutants spreading. An inconvenience connected with the use of the LEV is the need of placing them directly in the area of the dust emission sources. This is because of the fact, that the pollution capture elements – e.g. suction noz-

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zles – work efficiently in a small area. In rooms where pollution dusts are emitted, the local mechanical ventilation system should be supported by general mechanical ventilation system. Proper air distribution in the room with dust emission source is important for common operation of ventilation systems. Flow characteristics resulting from the operation of ventilation system has a great impact on pollutants spreading in the room. Thus, common operation of the LEV with general ventilation system should ensure efficient protection of operator working zone against pollutants.

The need of systematizing the knowledge concerning investigations of dust emissions from machines is best reflected by works of Technical Committee TC 114 of the European Committee for Standardization. The methods of tests and assessments of hazardous substances from machines were standardized and determined in standards of EN 1093 series. These standards, depending on the aim of testing, recommend using different test methods, which in consequence requires accounting for assessment parameters, test environment and the types of aerosols which simulate real pollution[4]. Depending on the kind of required information concerning airborne pollutants it is possible to determine flow rate of pollutants from machines, the working room contamination concentration, pollutant capture efficiency of the LEV and decontamination index of the system used for limiting contamination. Tests may be carried out in the laboratory conditions (in the test chamber or in the whole laboratory room) and in real conditions (in industrial areas on work places). To simulate dust emission from machines there may be used test dust or tracer gases having aerodynamic parameters close to real pollution parameters. The study of pollutants emission from various processes using tracer gases carried out in Poland[5–7] and in the world[8–21]. Although the use of test dust better reflects real conditions of pollution emission, the tests based on tracer gases enable to make measurements with higher accuracy because these tracers do not generally exist as a real air pollution which may, however, take place in case of test dusts.

Research on evaluation of emissions from machinery used for the treatment of losses, according to the method of test bench using tracer gases, are currently being conducted in CIOP-PIB. In this study, I focused on the influences of some parameters related to the flow characteristics on the pollutant capture efficiency of ventilation system during metal grinding. There, the bench tests were carried out to reveal relationships of the efficiency changes to variations of ventilation systems and emission sources by modified methods. The tests can serve for following three:

- the evaluation of the reduction of pollutants emission of the machine,
- the comparison of machines within groups of machines with the same intended use (e.g. grinders, sanders),
- the ranking of machines from the same group according to their emission rates.

Subjects and Methods

On the basis of the review of risks existing during machining, with a particular consideration of widespread use of machining in various industrial sectors in the world as well as its harmfulness, it was proposed to test dust emission generated during abrasive machining of metals. In Table 1 variable parameters configurations applied for testing pollutants emission from machines used to abrasive machining of metals, in the test chamber, are presented. The tests were carried out for 10 metal dust emission sources during the grinding of the closed profiles made of stainless steel AISI 304. In order to differentiate parameters characterising emission source, the examinations were carried out with the use of:

- four grinders (angle grinder, orbital sander, disc-belt grinder and eccentric grinder),
- two rotation speeds (U_1 and U_2),
- abrasive materials having two different shapes and five dimensions (D_1, D_2, D_3, $A_1 \times B_1$ and $A_2 \times B_2$).

Parameters enabling both assessment of pollutants emission from machines and assessment of working effectiveness of capture systems of pollutants are determined with the use of three measurement methods:

- smoke flow visualization method with the aim of indexing air movement as well as images registration and flow filming by digital camera,
- anemometric method with the aim to determine:
  - volume air flow rate in exhaust duct of capture system with the use of VelociCalc Model 8360 (TSI Inc., USA) anemometer, by the measurement of air velocity,
  - air flow distribution in the vicinity of tested object with the use of VIVO measurement kit (Dantec Dynamics, Denmark),
- tracer gas method enabling simultaneous measurement of:
  - mass real pollutant concentration with the use of DustTrak aerosol monitor Model 8520 (TSI, USA),
  - mass tracer gas concentration with the use of portable gas analyser MIRAN SapphIRe Model 100E (Thermo/Foxboro, USA).

The volume air flow rate in duct of the LEV is determined in accordance with the methods presented in

Table 1. Configuration of test sources of pollutant emission

Number of emission source	Type of grinder	Speed	Type of abrasive material	Dimensions of abrasive material	Type of tracer gas source
—	—	[min^{-1}]	—	[mm]	—
Z1	dual disc	U_1=1,360	disc	D_3=ϕ250	plane
Z2	angle	U_1=2,800	disc	D_1=ϕ125	volumetric
Z3	angle	U_2=11,000	disc	D_1=ϕ125	volumetric
Z4	eccentric	U_1=4,500	random orbit sander	D_1=ϕ125	volumetric
Z5	eccentric	U_2=12,000	random orbit sander	D_1=ϕ125	volumetric
Z6	orbital	U_1=7,000	orbital sander	A_1=93 × B_1=185	volumetric
Z7	orbital	U_2=12,000	orbital sander	A_1=93 × B_1=185	volumetric
Z8	disc	U_1=2,950	disc	D_2=ϕ150	plane
Z9	disc	U_1=2,950	belt sander	A_2=50 × B_2=686	plane
Z10	disc-belt	U_1=2,950	disc belt sander	D_2=ϕ150 A_2=50 × B_2=686	point

EN 12599:2000/AC:2002 standard[22)], and is calculated on the basis of average air velocity in the duct, determined as mean value from the results of air velocity measurements in chosen points of the duct cross section. Depending on the shape of duct cross section (e.g. circular or rectangular) and its dimensions, a different number of measurement points is appointed. The volume flow rate of air flowing through the exhaust duct (Q [m^3/h]) is calculated according to the following formula:

$$Q = 3600 \cdot F \cdot V_{p,śr} \tag{1}$$

where:

$V_{p,śr}$ is average air velocity in the duct cross section [m/s]

F is the duct cross section [m^2].

The measurement points in spatial grid of chamber are located in vertical and horizontal planes at the head height, the middle of operator's height and the feet height which corresponds to height of 1.7 m, 1.1 m and 0.1 m in case of a standing person.

The number and location of measurement points in the test chamber are presented in Fig. 1.

The tracer gas method consists in starting the machine and simultaneous introducing of the marker with a constant air flow rate in a chosen point of real pollutants emission, and then determining concentrations real pollutants and tracer gas in points, located in the chamber in accordance with the standard EN 1093-2:2006+A1:2008[23)] (Fig. 1). The volume flow rate of tracer gas is adjusted with the use of a set of flow meters. In the source of emission of real pollutants, the probe for tracer gas dosing is placed. The following are used:

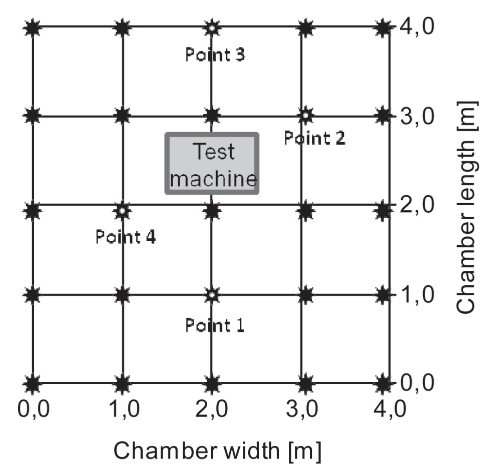

Fig. 1. Location of measurement points of air velocity rate and tracer gas concentrations in the test chamber.

- point sources that may be simulated with the use of open pipes generating streams having variable aerodynamic characteristics or with the use of sintered materials that disperse the tracer gas at small initial speed value,

- plane and volumetric sources, which may be simulated with the use of spot sources system or perforated tubes, suitably deployed.

The direction and volume air flow rate of tracer gas flowing from the probe should be the same as the direction and volume air flow rate of real pollutants.

According to the EN 1093-2:2006+A1:2008[23] standard, the mass tracer gas flow rate from machine with capture system turned on $(q_{wl,T,i})_m$ [mg/s] in a given measurement point is calculated with the use of the following relation:

$$(q_{wl,T,i})_m = (q_{T,i})_V \cdot \frac{M_T \cdot 1000}{V_{m(t,p)} \cdot 60} \tag{2}$$

where:

$(q_{T,i})_V$ is the volume tracer gas flow rate [l/min] in the given measurement point "i"

M_T is the molar mass of tracer gas [g/mol]

$V_{m(t,p)}$ is the molar volume of gas at the temperature (t) and pressure (p) of the experiment [l/mol].

The mass pollutant emission rate from machine with capture system turned on $(q_{wl,p,i})_m$ [mg/s] is calculated according to the following relation:

$$(q_{wl,p,i})_m = (q_{wl,T,i})_m \cdot \frac{\sum_i \frac{(\bar{C}_{wl,p,i})_m}{(\bar{C}_{wl,T,i})_m}}{n} \tag{3}$$

where:

$(\bar{C}_{wl,p,i})_m$ is the mean mass concentration of real pollutant [mg/m^3]

$(\bar{C}_{wl,T,i})_m$ is the mean mass concentration of tracer gas [mg/m^3]

n is the number of concentration measurement points.

The above steps and calculations are repeated for capture system turned off. The capture efficiency (η_c) [%] is determined by comparison of mass pollutant emission rate in machine surrounding for different variants of combined operation of general and local ventilation systems in test chamber.

$$\eta_c = \frac{\left[(q_{wyl,p})_m - (q_{wl,p})_m\right]}{(q_{wyl,p})_m} \cdot 100 \tag{4}$$

where:

$(q_{wyl,p})_m$ is the mass pollutants emission rate with capture system turned off [mg/s]

$(q_{wl,p})_m$ is the mass pollutants emission rate with capture system operating jointly with a chosen variant of general ventilation system [mg/s].

As part of investigations, additional elements modifying turbulent air velocity field (air flow forcing in the vicinity of pollutant emission sources) in the test chamber were introduced, in order to get representative air distribution for particular machining variants. Five variants of combined operation of general and local ventilation systems were applied on test stand:

- M variant - ventilation turned off

the test machine only works

- W1 variant – the LEV

the LEV limits the pollutants spreading through dominance of local air flow to the capture system. Due to the capture system location it influences air flow in the pollutants emission source environment. The test stand was equipped with the LEV system CT 22E (Festool, USA). A nozzle extracting pollutants from the machine is connected with end fitting of the LEV system by round flexible hose with the diameter of ø 0.027 m × 3.5 m. The air together with dust pollutants is drawn in pollutant emission source and directed to a dust separator located outside the test chamber. Then the air after being cleaned in a filter is extracted outside the laboratory. Below there are presented technical specifications of CT 22E system:

maximum flow rate value – 228 m^3/h
maximum vacuum pressure – 23,000 Pa
filtration area – 14,000 cm^2

- W2 variant – one-way general ventilation and the LEV

one-way general ventilation system generates air streams with pollutants suspended inside. They are extracted outside the pollutants emission source area by centrifugal fan. This fan is fitted in ventilation duct behind the test chamber.

- W3 variant – mixing type of general ventilation and the LEV

mixing type of general ventilation system induces the air mixing process in the test chamber as a result of mechanical supply streams domination. The test stand was equipped with centrifugal fan fitted behind the test chamber and axial-flow fan placed on the floor in the centre of inlet plane to the test chamber.

- W4 variant – positive displacement type of general ventilation and the LEV

as a result of positive displacement type general ventilation system operation the different flow zones are being isolated, circulation flows are created, and thermal stratification in pollutants emission source surround-

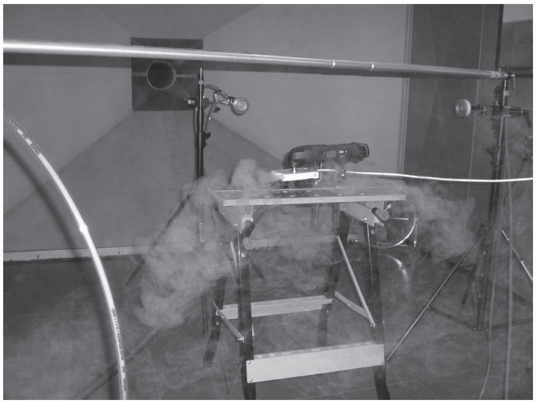

Fig. 2. Smoke flow visualization near angle grinder – grinding disc's rotation speed U_1, volume emission source and ventilation turned off (M variant).

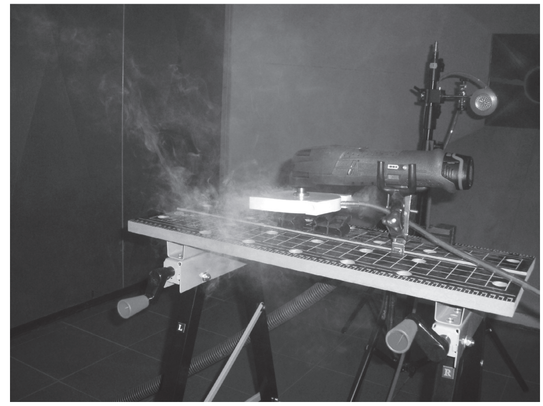

Fig. 3. Smoke flow visualization near angle grinder – grinding disc's rotation speed U_1, volume emission source and positive displacement type of general ventilation and the LEV turned on – W4 variant.

ing appears. The test stand was equipped with the two axial-flow fans placed on the floor on the diagonal connecting two opposite corners of the test chamber.

Results

The results are shown in the example of the emissions test with angle grinder. The tested grinder was used mainly for grinding of metal in workshop. The angle grinder was equipped with one grinding disc with the possibility of pollutant exhaust from the source. The angle grinder was equipped with fixed pollutants capture system.

Smoke flow visualization

The observation results of smoke flow visualizations within the area of grinder operation depending on used flow distributions in the test chamber were presented in Figs. 2 and 3. Visualization of smoke flow shows that there was an inflow of air caused by grinding disc's rotation movement (Fig. 2). Switching on the LEV system caused the stream separation into two parts. One part of the stream was directed to the exhaust inlet surface and the remaining part was directed as follows:

- to the floor in the plane of points No. 3 and 4 - W1 variant
- to the floor in the plane of points No. 1 and 3 - W2 variant
- to the floor in the plane of points No. 3 - W3 variant
- upwards in the plane of points No. 3 and 4 - W4 variant (Fig. 3).

Air velocity measurements

Figure 4(A) and 4(B) show the examples of air velocity distributions in the No. 2 pollutant emission source surrounding depending on measurement planes are presented. On the basis of an analysis of the data presented in Fig. 4(A) and 4(B) it was found that:

a) ventilation turned off (M variant) – inflow of air stream from the emission source to the floor of test chamber, air velocity increase in central zone of the test chamber (the emission source surroundings), maximum air velocity values were changing from 0.12 m/s (operator's breathing zone), through 0.43 m/s (emission source) to 0.40 m/s (test chamber floor), in the areas not affected by the air stream the air velocity changed from 0.05 m/s to 0.10 m/s,
b) ventilation W1 variant – lower air velocity differentiation in the grinder's and the LEV's operation zone, in the range of 0.06–0.17 m/s, inflow of the air stream from the emission source to the floor of test chamber (the plane of points No. 3 – 0.16 m/s and No. 4 – 0.17 m/s), in the areas not affected by the air stream the air velocity changed from 0.05 m/s to 0.09 m/s,
c) ventilation W2 variant – high air velocity differentiation in the zone of planes from 0.5 m to 2.5 m in the range from 0.09 m/s to 0.53 m/s, inflow of air stream was caused by the grinder's operation – zone from the emission source to the floor of test chamber (the plane of points No. 1 – 0.27 m/s and No. 3 – 0.37 m/s), air velocity increase was also observed in the interaction zone of the one-way general ventilation system (0.29–0.53 m/s), in the areas not affected by this stream the air velocity changed from 0.05 m/s to 0.09 m/s,
d) ventilation W3 variant – high air velocity differentiation in different points of the test chamber, the air velocity changed from 0.05 m/s to 3.29 m/s, inflow of air stream was caused by the mixing ventilation system, air velocity nearby the extraction nozzle was

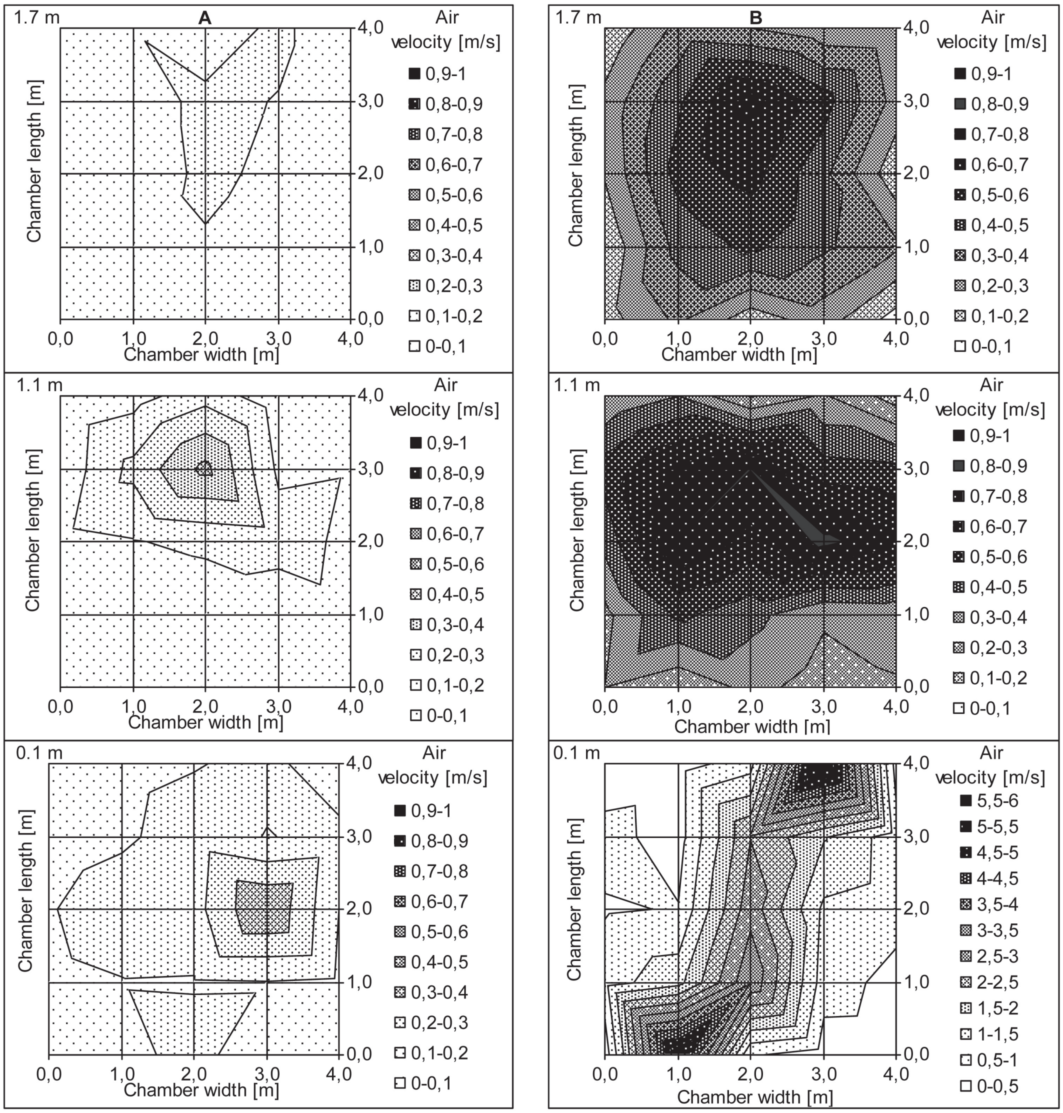

Fig. 4. Characteristics of air velocity distributions within the area of grinder operation at height of 1.7 m, 1.1 m and 0.1 m.

(A) - ventilation turned off (M variant), (B) - positive displacement type of general ventilation and the LEV turned on – W4 variant.

equal to 5.30 m/s,

e) ventilation W4 variant - high air velocity differentiation in different points of the test chamber, the air velocity changed from 3.44 m/s (the plane of floor) through 0.81 m/s (the plane of emission source) to 0.74 m/s (operator's breathing zone), the air stream inflow to central zone of the test chamber and directed to upper planes of the test chamber, air velocities nearby the extraction nozzles were equal to 5.44 m/s and 5.85 m/s.

Tracer gas test

Measurements of the real pollutant and tracer gas average mass concentrations at the time of angle grinder machining with the speed U_1 in the test chamber were executed in the following laboratory environment conditions;

temperature: 20.5–20.6 °C

relative humidity: 56.6–56.9 %

atmosphere: 1003.6–1003.9 hPa.

To evaluate the pollutants emission in the process of grinding metal products sulfur hexafluoride 3.0 (SF_6) was selected as a tracer gas. During testing SF_6 was emitted with constant rate stream $(q_T)_V$ equal to $5.12 \cdot 10^{-3}$ m^3/h (with measurement uncertainty 2.95%). Whereas measured real pollutant volume stream $(q_p)_V$ was 4.98·10–3 m^3/h (with measurement uncertainty 6.00%). In Figure 5 the changes of the SF_6 concentra-

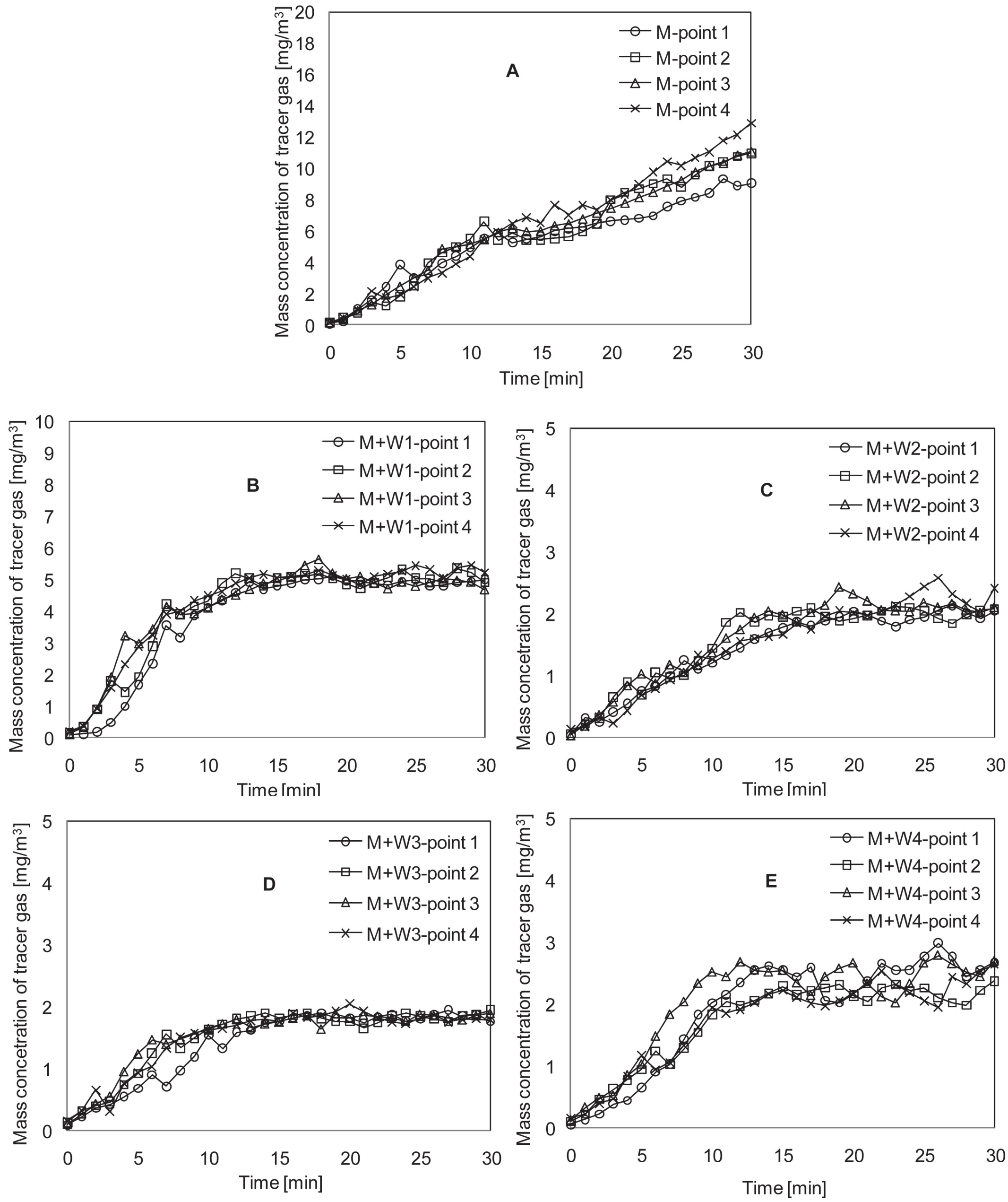

Fig. 5. Distribution of tracer gas concentration at four measurement points around angle grinder.
(A) - ventilation turned off, (B) - the LEV turned on, (C) - one-way general ventilation and the LEV turned on, (D) - mixing type of general ventilation and the LEV turned on, (E) - positive displacement type of general ventilation and the LEV turned on.

tion, depending on the test chamber flow characteristics, were presented. Measurement data obtained enabled to define real pollutants and tracer gas average mass concentration for various flow characteristics of the test chamber. Determination of the real pollutants and tracer gas concentration in the tested object's surroundings enabled to determine the value of pollutants mass flow rate from the angle grinder for different flow characteristics in the test chamber. Moreover, the efficiency of pollutants capture from the angle grinder with the use of applied the LEV was determined (Table 2). The results of the pollutants and tracer gas concentration measurements show that the curves presenting changes of the mass concentration of metal dust as the function of time (Fig. 6) were similar to the curves presenting changes of SF_6 mass concentration as the function of time (Fig. 5). The graphs of metal dust and SF_6 mass concentration changes in the environment of angle

Table 2. Results of capture efficiency of the LEV and mass pollutants emission rate from the angle grinder (speed U_1) for different flow characteristics in the test chamber

Variant of flow characteristics in the chamber	$\frac{(\bar{C}_{p,i})_m}{(\bar{C}_{T,i})_m}$				$\frac{\sum_i \frac{(\bar{C}_{p,i})_m}{(\bar{C}_{T,i})_m}}{n}$	$(q_p)_m$	η_c
	Point 1	Point 2	Point 3	Point 4	—	[mg/s]	[%]
ventilation turned off (M)	0.87	0.93	0.98	0.97	0.94	8.02	—
ventilation W1	0.12	0.12	0.13	0.13	0.13	1.06	86.74
ventilation W2	0.11	0.11	0.11	0.12	0.11	0.94	88.34
ventilation W3	0.08	0.08	0.08	0.08	0.08	0.65	91.86
ventilation W4	0.10	0.11	0.10	0.10	0.10	0.88	89.00

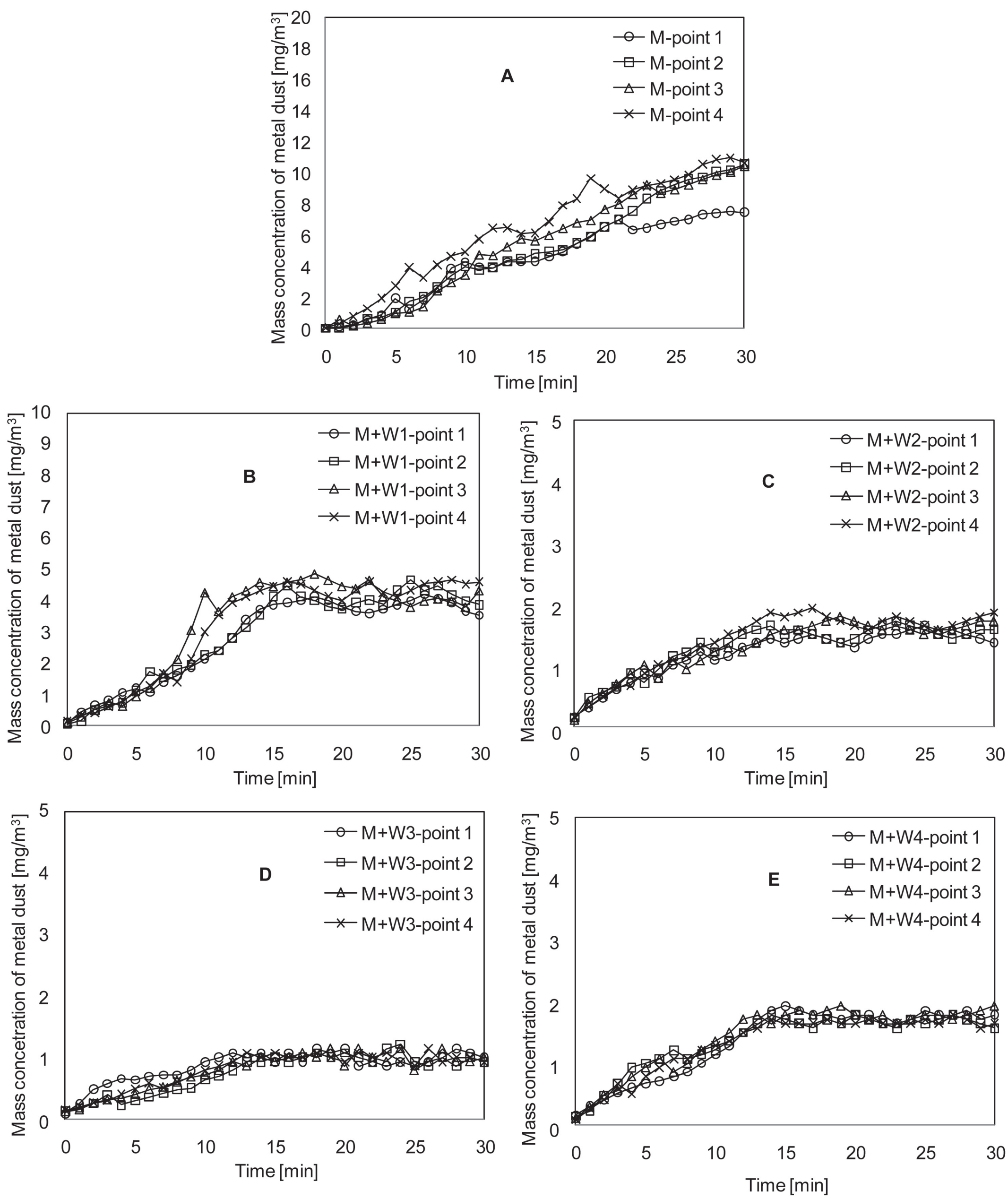

Fig. 6. Distribution of metal dust concentration at four measurement points around angle grinder.
(A) - ventilation turned off, (B) - the LEV turned on, (C) - one-way general ventilation and the LEV turned on, (D) - mixing type of general ventilation and the LEV turned on, (E) - positive displacement type of general ventilation and the LEV turned on.

grinder with switched off general ventilation and the LEV may be divided into two stages – background and concentration increase (Figs. 5A and 6A). Curves illustrating the changes of metal dust and SF_6 mass concentration in the angle grinder environment had similar character, irrespective of the flow characteristics used in the test chamber – three stages – background, concentration increase and stabilization (Figs. 5B–5E and 6B–6E). Separate stages of real pollutant and tracer gas distribution were characterised by different ranges of mass concentration values. In the case of W1, W2, W3 and W4 variants, in all measurement points, rather steady distributions of mass concentration of pollutants were observed. Based on the results presented in Table 2 it was observed that:

a) in all W variants of ventilation a decrease of pollutant mass emission values was obtained,
b) the highest pollutant mass emission was observed in the case of W1 variant – 1.06 mg/s, and the lowest one was observed in the case of W3 variant – 0.65 mg/s,
c) in the case of W1, W2, W3 and W4 variants the average values of the tracer gas concentration were accordingly: 5.03 mg/m^3 (W1), 2.03 mg/m^3 (W2), 1.82 mg/m^3 (W3) and 2.35 mg/m^3 (W4),
d) the capture efficiency was changing in accordance with the type of combined operation of general and local ventilation systems and it fluctuated from 86.74% to 91.86%.

Discussion

In the investigations of pollutants emission from machines used for metal machining in laboratory conditions, of great importance are visualization and anemometric measurement methods of air flows. These methods allow for imaging and determination of the role of particular flow characteristics in the environment of pollutants dispersion from the source of emission.

Test results analysis demonstrated an influence of flow characteristics changes in the test chamber on parameters connected with pollutant emission during metalworking with the use of chosen grinders. Visualization of smoke flow during metalworking with the use of grinders in case of switched off ventilation system shows that an air stream inflow forced by rotation speed of material sample working elements appeared. Switching on the LEV system caused the stream separation into two parts. One part of the stream was directed to exhaust's inlet surface and the remaining part was directed to the emission source environment. Directed air flow from the emission source to the exhaust was highly deformed by general ventilation system in the degree dependant on the variant used during testing. The photographs and videos made with registered air flows show the complexity and diversity of influences forming the air flows in the surroundings of the tested pollutants emission sources. An analysis of visualization data definitely facilitated proper interpretation of air velocity distributions and real pollutants and tracer gas concentrations test results.

On the basis of tests of air velocity distributions in the surroundings of tested object it appears that the air stream directions change both in horizontal and vertical planes with the distance from emission source. In case of switched off ventilation (M variant), the air stream inflow from emission source to test chamber floor was observed, with simultaneous increase of air velocity only in the central zone of the test chamber. The use of the LEV in W1 variant results in air velocity differentiation nearby grinder operation and exhaust zone. Directed air stream from the emission source to the exhaust was highly disturbed by combined operation of ventilation systems in W2, W3 and W4 variants, which caused higher differentiation of air velocity in the wider range of measuring planes in the chamber. Dominant role was played by the elements modifying air flow area in the surroundings of tested emission sources.

The evaluation of the reduction of pollutants emission of the machine

The defined distributions of metal dust and SF_6 mass concentration in the angle grinder environment with switched off general ventilation and the LEV had similar characteristics - divided into the two stages – background and concentration increase. On the other hand, curves illustrating changes of metal dust and SF_6 mass concentration in the angle grinder environment had similar character, irrespective of the flow characteristics used in the test chamber – three stages – background, concentration increase and stabilization. Except for the first pollutants emission source (emission source No. Z1 – disc grinder with the highest tested grinding disc diameter D_3) in all the remaining sources, rather smooth distributions of simulated mass concentrations of pollutants with the use of tracer gas in all measurement points inside the test chamber were observed. This may indicate that pollutants not caught by the exhaust were evenly dispersed in the emission source surroundings. In case of testing emission source No. Z1 for W1 and W2 variants, the increased values of pollutants mass concentrations in the zones of two measurement points (points No. 3 and 4) were observed. This can prove that the local pollutants cumulate in the surroundings of emission source which may consequently create increased risk from the metal dust in the grinder opera-

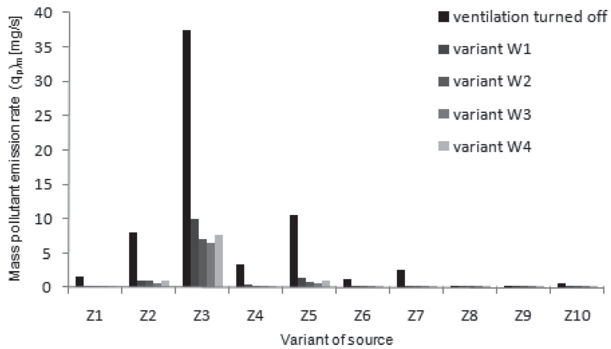

Fig. 7. Mean mass pollutants emission rates for tested variants of sources and ventilation.

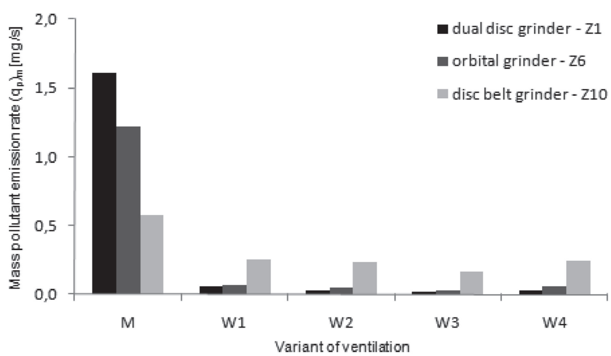

Fig. 8. Mean mass pollutants emission rates from dual disc, orbital and disc belt grinders for different variants of ventilation.

tor's working zone.

The ranking and the comparison of machines from the same group according to their emission rates

In Figures 7 and 8 the measuring results of mass flow rate of metal dust during grinding operation represented by 10 sources for different variants of combined operation of general ventilation with LEV were presented. In all analysed cases the highest values of emission flow rates were observed in case of ventilation system turned off. Taking as an emission index its mass pollutants emission rate, three groups of emission sources may be distinguished:

- large emission flow rate values in the range of 8.02–37.43 mg/s - Z2, Z3 and Z5 sources,
- medium emission flow rate values in the range of 1.22–3.39 mg/s - Z1, Z4, Z6 and Z7 sources,
- small emission flow rate values in the range of 0.14–0.58 mg/s - Z8, Z9 and Z10 sources.

Presented data can prove the influences of machine type (machining process with the use of angle grinder - 8.02 mg/s, and orbital grinder - 1.22 mg/s) and the rotation speed value of moving elements (machining process with the use of eccentric grinder with rotation speed U_1 - 3.39 mg/s and with the rotation speed U_2 - 10.49 mg/s) on the increase of metal dust emission hazard.

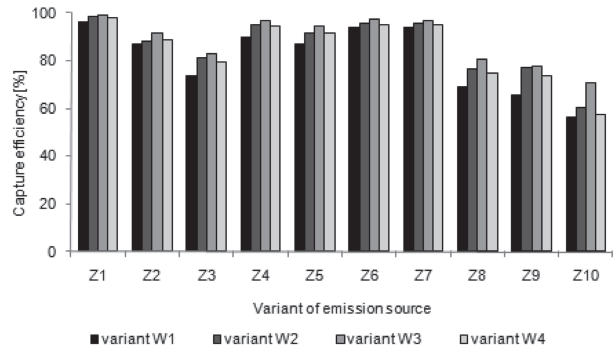

Fig. 9. Mean capture efficiency rates for tested variants of sources and ventilation.

Figure 9 shows the overall results of the influence of flow characteristics in the surroundings (combined operation of general ventilation with LEV) on the efficiency of the exhaust with tested emission sources. The capture efficiency was changing accordingly with the type of combined operation of general and local ventilation systems and it was fluctuating in the range of 56.59% to 98.87% (Fig. 9). An increase in the efficiency of dust capture depending on the source of emission by 2.5–14% was observed (Fig. 9). The most effective combined operation of general and local ventilation system was used in the metal grinding process with the use of disc grinder of disc diameter D_3 ($\eta_{c,1}$=97.90%). The least effective system was used in the metal grinding process with the use of disc - belt grinder of disc diameter D_2 ($\eta_{c,10}$=61.31%). Comparison of average capture efficiency values for the individual ventilation variants shows that formation of air movement as a result of combined operation of general mixing ventilation and the LEV systems enables to capture metal dust with 89% efficiency (Fig. 9). It was found that the least efficient variant is pollutants capture with the use of the LEV only.

Conclusions

On the basis of conducted tests it may be stated that pollutant capture efficiency directly from the pollutant source is connected with three parameters:

- volume air flow rate ensuring efficient pollutants capture from the emission source to the suction nozzle of the LEV,
- mass pollutants emission rate characterised by pollutant concentration distribution in the source surroundings,
- air flow direction and air velocity distribution influencing pollutants transport in the emission

source surroundings and the operation zone of the LEV.

The relation between the above parameters and pollutants capture efficiency depends to a large extent on the general ventilation system variant used. Therefore, proper combined operation of all elements modifying air flow and pollutants dispersion in the surroundings of the LEV is very important for effective pollutants capture from the emission sources.

Assessment of the influence of the above parameters in pollutant emission source surroundings allows both machine manufacturers and the employees of operation services of the LEV systems used in metal machining processes, to support designing of the new constructions of the LEV systems or improve activities aimed at increasing efficiency of LEV systems operating in combination with machines.

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References

1) American Conference of Industrial Hygienist (2007) Documentation of the TLVs and BEIs with Other Worldwide Occupational Exposure Values. AGHIH, Cincinnati.
2) Ministry of Labour and Social Policy (2009) Assessment of health and safety at work, Warsaw.
3) American Conference of Industrial Hygienist (2010) Industrial ventilation: a manual of recommended practice for Design, 27th Ed., ACGIH, Cincinnati.
4) EN 1093-1 (2008) Safety of machinery - Evaluation of the emission of airborne hazardous substances - Part 1: Selection of test methods. European Committee for Standardization, Brussels.
5) Gliński M (2002) Dust emission and efficiency of local exhaust ventilation during cast iron grinding. Int J Occup Saf Ergon **8**, 95–105.
6) Jankowski T, Jankowska E (2004) Investigation of the aerosol emission using tracer gas method. J Aerosol Sci **2**, 1145–46.
7) Jankowski T, Jankowska E (2007) Investigation of air pollutants dispersion at workstands. Sigurnost **49**, 1–7.
8) Niemelä R, Lefevre A (1991) Comparison of three tracer gases for determining effectiveness and capture efficiency. Ann Occup Hyg **35**, 405–17.
9) Fletcher B, Johnson A (1992) Ventilation of small factory units. J Wind Eng Ind Aerodyn **40**, 293–305.
10) Dessagne JM, Lefèvre A, Muller JP (1993) Synthesis of results obtained using the tracer gas technique. In: Hughes RT, Goodfellow HD, Rajhans GS (Eds.), 505–14, Ventilation'91. ACGIH, Cincinnati.
11) Breum NO (1993) Diagnosis of Ventilation by Single-Tracer Gas Techniques. Indoor Air **3**, 5–28.
12) Jung A, Zeller M (1994) An analysis of different tracer gas techniques to determine the air exchange efficiency in a mechanically ventilated room. Fourth International Conference Roomvent'94, Kraków **2**, 315–32.
13) Madsen U, Aubertin G, Breum NO, Fontaine JR, Nielsen PV (1994) Tracer gas technique versus a control box method for estimating direct capture efficiency of exhaust systems. Proceedings of the 4th International Symposium on Ventilation for Contaminant Control, 333–38, NIOSH, Cincinnati.
14) Mosovsky JA (1995) Sulfur hexafluoride tracer gas evaluations on hood exhaust reductions. Am Ind Hyg Assoc J **56**, 44–9.
15) Bémer D, Lecler MT, Régnier R, Hecht G, Gerber JM (2002) Measuring the emission rate of an aerosol source placed in a ventilated room using a tracer gas: influence of particle wall deposition. Ann Occup Hyg **46**, 347–54.
16) Moore RW (2004) Tracer gas testing applications for industrial hygiene evaluations. Occup Hazards **66**, 39–43.
17) Beamer D, Muller JP, Dessagne JM (2004) Comparison of capture efficiencies measured by tracer gas and aerosol tracer techniques. Indoor Air **8**, 47–60.
18) Ojima J (2007) Tracer gas evaluation of local exhaust hood performance. San Ei Shi **49**, 209–15 (in Japanese with English abstract).
19) Ahn K, Woskie S, DiBerardinis L, Ellenbecker M (2008) A review of published quantitative experimental studies on factors affecting laboratory fume hood performance. J Occup Environ Hyg **5**, 735–53.
20) Ojima J (2009) Tracer gas evaluations of push-pull ventilation system performance. Ind Health **47**, 94–6.
21) Bell G (2009) Predicting gaseous pollutant dispersion around a workplace. J Chem Health Saf **16**, 14–9.
22) EN 12599:2000/AC:2002. Ventilation for buildings - Test procedures and measuring methods for handing over installed ventilation and air conditioning systems. European Committee for Standardization, Brussels.
23) EN 1093-2:2006+A1:2008. Safety of machinery - Evaluation of the emission of airborne hazardous substances - Part 2: Tracer gas method for the measurement of the emission rate of a given pollutant. European Committee for Standardization, Brussels.