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RELATIONSHIP BETWEEN ODOUR INTENSITY AND ODORANT CONCENTRATION: LOGARITHMIC OR POWER EQUATION

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ZALEŻNOŚĆ INTENSYWNOŚCI ZAPACHU OD STĘŻENIA ODORANTÓW: RÓWNANIE LOGARYTMICZNE CZY POTĘGOWE

Podczas ocen uciążliwości zapachowej wykorzystywane są prawa psychofizyczne – logarytmiczne prawo Webera-Fechnera i potęgowe prawo Stevensa. Celem niniejszej pracy było stwierdzenie lub wykluczenie przewagi jednego z tych praw. W celu oceny praw psychofizycznych wykonano serię pomiarów odorymetrycznych wodnych roztworów kwasu octowego. Wyznaczono wartości współczynników korelacji liniowej Pearsona dla zależności intensywności zapachu (I) od logarytmu stężenia kwasu octowego nad roztworem ($\log_{10} C$ [mg/m^3]) oraz dla zależności logarytmu intensywności zapachu ($\log_{10} I$) od logarytmu stężenia kwasu octowego nad roztworem ($\log_{10} C$ [mg/m^3]). Oba prawa psychofizyczne są równie dobrze spełniane w zakresie badanych stężeń kwasu octowego.

Summary

Assessments of odour nuisance are made using one of the psychophysical laws: logarithmic Weber-Fechner law or power law by Stevens. The object of the work was to determine whether one of the laws exhibits advantage over the other. To evaluate the two laws series of odorimetric measurements of aqueous solutions of acetic acid were made. Values of Pearson' correlation coefficient were calculated for relationship of the odour intensity (I) versus logarithm of the acetic acid concentration in air ($\log_{10} C$ [mg/m^3]) as well as for the relationship of logarithm of the odour intensity ($\log_{10} I$) versus logarithm of the acetic acid concentration in air ($\log_{10} C$ [mg/m^3]). Both laws are fulfilled equally well in a range of investigated concentrations of acetic acid.

INTRODUCTION

The results of the odorimetric measurements of the pollutant concentrations in industrial off-gases are used to calculate the concentrations that can occur in different distances from the source. The concentration forecasts enable predictions of odour intensities as well as the emmitor nuisance rank [9, 10].

The basic procedures for odorimetric measurements and calculations are based on psychophysical Weber-Fechner law [8]. The law assumes that the constant just noticeable difference (JND) occurs between two compared stimuli magnitudes. According to the law the change of the odour intensity should be proportional to relative change of the odorant concentration. Thus:

$$I = k \cdot \log TON$$

where: I – odour intensity, TON – threshold odour number (odorant concentration) [ou/m^3], k – Weber-Fechner coefficient.

The Weber-Fechner law is commonly used for the formation of scales of the sensory sensation intensity standards [3, 6, 7]. Differences between the taste intensities of the consecutive taste stimuli standard solutions are regarded as equal if concentrations of the solutions form geometrical series. The same rule is applied for odour intensity standards.

The scales of odour intensity standards formed that way are linear if the logarithmic law of Weber-Fechner is met. This is confirmed by the following equations:

$$TON_i = TON_0 \cdot (K)^i$$
$$TON_{i+1} = TON_0 \cdot (K)^{i+1}$$
$$I_i - I_{i+1} = k \cdot (\log TON_i - \log TON_{i+1})$$
$$I_i - I_{i+1} = - k \cdot \log K = const$$
$$I_i - I_{i+1} = \text{const (scale is linear if } K \text{ and } k \text{ are constant)}$$

where:

K – step of dillution (factor of the concentrations geometric series),
TON_0, TON_i and TON_{i+1} – concentrations of the basic, i and $i+1$ samples.
I_i and I_{i+1} – odour intensities of i and $i+1$ samples.

The psychophysical research made by Stevens led to a conclusion that the logarithmic law fits the data worse than the power law [13]. The power law is represented by the equation:

$$I = k_s \cdot S^n$$

where:

S – physical intensity,
k_s, n – empirical constants,

less frequently by the equation [14]:

$$I = k_s \cdot (S - S_0)^n$$

where:

S_0 – threshold stimulus.

Psychophysicists [4, 5, 15] almost exclusively use the power law. Some publications though describe the logarithmic and power laws as equal [12, 14]. The literature lacks the clear-cut verification of the equations with reference to perceived odour intensity. The results of the first stage of our research on the topic are presented below.

MATERIALS AND METHODS

SUBJECTS

Sixteen university students participated in the experiment. They were 22 – 25 years of age. None of them had any previous experience in olfactory experiments. They were not informed about the purpose of the experiment.

APPARATUS

The stimuli were presented in an odour laboratory. The laboratory consisted of the test chamber, waiting room (clean part) and the chemical laboratory (unclean part) where the samples were prepared. The clean part of the laboratory was equipped with the high efficient ventilation and air-conditioning system. The clean and unclean parts of the laboratory had their own entrances. The only connection between the parts was the window through which the samples were given to the subjects.

STIMULUS

The odorous substance used in the experiment was aqueous solution of the acetic acid. It was chosen because of the fact that the smell of the acid is well recognisable thus subjects can concentrate only on odour magnitude evaluation. The acid concentration in the air over the solution was calculated using the liquid-vapour equilibrium data [11]. It was established that the concentrations of the acid in the air over the solutions in 20°C are within the range of 60 – 1400 mg/m^3.

PROCEDURE

20 cm^3 of each concentration of the odour stimulus was placed in 50 cm^3 polyethylene squeeze bottles. Each bottle was tightly closed to form the liquid-vapour equilibrium state. We assumed that the equilibrium establishes 3 – 5 minutes after the bottle is closed. The subjects opened the bottle and squeezed it directing the vapour into the chosen nostril. Two methods of odour intensity estimations were applied. The point scale method consisted in attributing the consecutive scale ranks to the verbal descriptions of the odour intensity (0 – not smellable, 1 – very low, 2 – low, 3 – medium, 4 – strong, 5 – very strong). The collected opinions of the subjects were used to determine the median value.

The "proportion method" consisted in presenting three different acetic acid concentrations. The subjects compared the intensity of the N sample (N_1 or N_2) to the intensities of the A and Z samples (A – lower odour, Z – stronger odour). The subjects' opinions were recorded by marking the off-distance on the slip of paper of 100-mm length. The ends of the paper slip were marked A and Z. For the purpose of the results interpretation the intensity $I_A = 1$ was attributed to the A sample and the Z sample intensity was $I_z = 2$. The N_1 and N_2 samples' intensities were the appropriate values from the $1 \div 2$ range. To calculate the values the AN_i sections were measured for each subject, then the L_{Ani}/L_{AZ} ratios (proportion) were calculated and the median of the $I_{Ni} = 1 + l_{ANi}/l_{AZ}$ values set were determined.

CALCULATIONS

The comparison of the two psychophysical laws was conducted by calculation of the Pearson correlation coefficient for relationship of the logarithm of the acetic acid concentration in air ($\log_{10} C$ [mg/m^3]) versus the odour intensity (I) and versus the logarithm of the odour intensity ($\log_{10} I$). The Pearson coefficients were calculated for the function I vs. $\log_{10} C$:

$$I = k \cdot \log_{10} (C/C_0)$$

$$I = const_1 \cdot \log_{10} C + const_2$$

and for the $\log_{10} I$ vs. $\log_{10} C$ function:

$$I = a \cdot (C - C_0)$$

$$\log_{10} I = const_3 \cdot \log_{10} (C \cdot C_0) + const_4$$

Higher values of the Pearson correlation coefficient for one of the functions would confirm the advantage of the respective law. Preliminary calculation were made with assumption that the odour threshold for acetic acid (C_0):

- can be omitted in respect to assessed samples concentration ($C >> C_0$; $C - C_0 \approx C$),
- equals 1.2 mg/m^3 according to Amoore and Hautala [2];
- can be calculated using Weber – Fechner equation:

$$I \rightarrow 0 \text{ when } log_{10}(C/C_0) \rightarrow 0 \text{ then } C \rightarrow C_0$$

RESULTS

The results of the measurements obtained by the "proportion method" are presented on figure 1. The acetic acid concentrations in samples A, Z, N_1 and N_2 were 125 mg/m^3, 659 mg/m^3, 189 mg/m^3 and 385 mg/m^3 respectively.

The Pearson correlation coefficient calculated for the function I vs. $\log_{10} C$ was slightly higher than the value calculated for the function $\log_{10} I$ vs. $\log_{10} C$ ($r = 0.99$ and $r = 0.98$ respectively).

Figures 2 and 3 present the results of the research made by the "point method". The distributions of the independent, individual assessments of the odour intensity of the four acetic acid concentrations (62, 157, 659 and 1406 mg/m^3) are shown in figure 2.

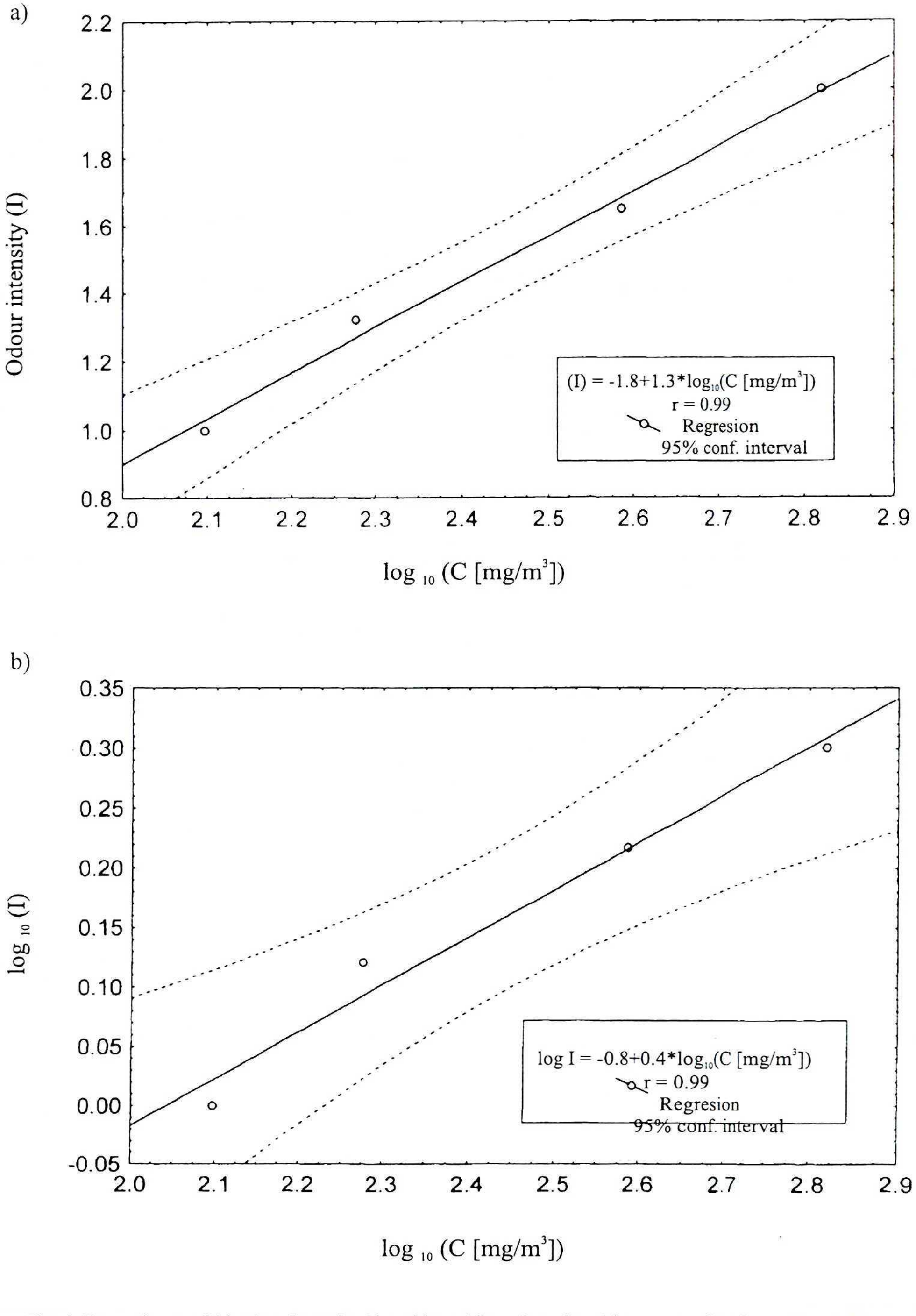

Fig. 1. Dependence of (a) odour intensity (*I*) and logarithm of acetic acid concentration ($log_{10}C$) and (b) of logarithm of odour intensity ($log_{10}I$) on logarithm of acetic acid concentration ($log_{10}C$). Values of odour intensity were obtained using the "proportion method"

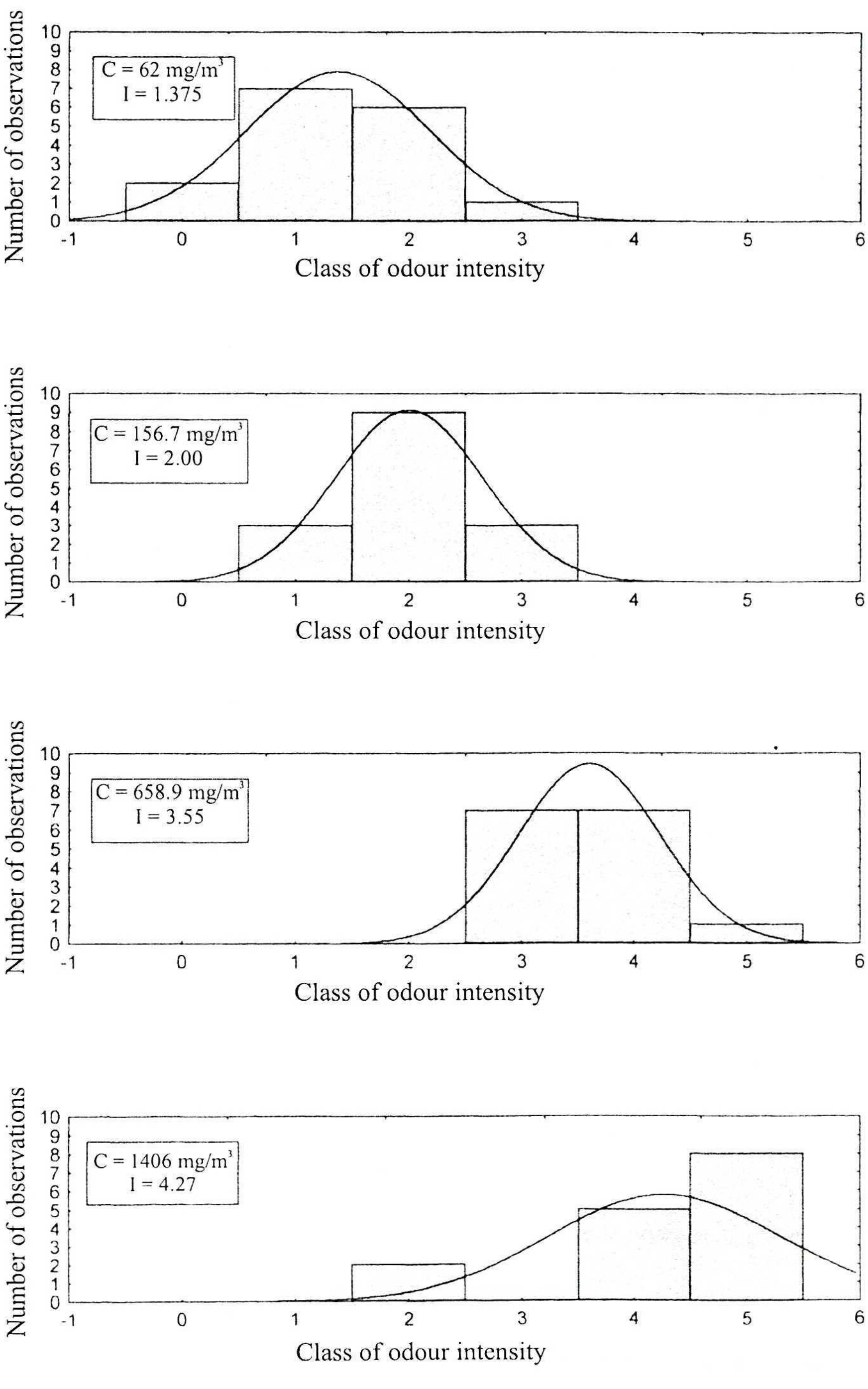

Fig. 2. Results distributions of individual assessments of odour intensity (*I*) obtained using the "point method". Subjects assessed four concentrations of acetic acid

The correlation between the median value of the assessments and the logarithm of the acetic acid concentration, $\log_{10}C$, is illustrated in figure 3a. The correlation coefficient for the function was r = 0.99 and equalled the respective value for the dependence $\log_{10}I$ vs. $\log_{10}C$ – the difference occurred on fourth decimal place (fig. 3b).

Two determined empirical equations:

$$I = -2.7 + 2.2 \cdot \log (C\ [\mathrm{mg/m^3}])$$

and

$$I = 0.3 \cdot (C\ [\mathrm{mg/m^3}])^{0.4}$$

are fulfilled within the entire measurement range ($I = 1.3 \div 4.5$). The extrapolation beyond that range, toward the lower concentrations allowed calculation of the threshold $C_0 = 16.3\ \mathrm{mg/m^3}$.

The threshold is almost ten times higher than the average value determined by using different methods: $C_0 = 1.2\ \mathrm{mg/m^3}$ [2].

The two values of the threshold C_0 were put into the Stevens' equation. The correlation coefficients for the dependence of the $\log_{10}I$ against $\log_{10}(C - 16.3)$ and against $\log_{10}(C - 1.2)$ were of the same value 0.99 (fig. 4). The values match the value calculated with $C - C_0 \approx C$ assumption (difference on the fourth decimal place). The functions $I = f(C)$ are presented graphically in figures 5 and 6.

DISCUSSION

We analysed results in order to find answers to the following questions:

1. Can we consider the samples of odorous substance whose concentrations form geometric series the standards of linear odour-intensity scale?
2. Can we predict the odour intensity in surroundings of the pollutants emitor using Weber-Fechner law: $I = k \cdot \log_{10}TON$?
3. Can we use the extrapolation toward $I = 0$ to determine the threshold (or TON)?

For the acetic acid odour intensity range $I = 1.5 \div 4.5$ (according to the six-step scale 0 – 5) the functions I vs. $\log_{10}C$ and $\log_{10}I$ vs. $\log_{10}C$ are characterised by very similar, high correlation coefficients. Therefore the relationship between the odour intensity (I) and the concentration of the acid in the air (C) can be expressed with both power and logarithmic equation.

Assuming that the conclusion is proved for another air pollutants we will prove that:

- it is possible to use Weber-Fechner equation for assessment of the impact of odorant emission on the air quality in surrounding of the pollutants source;
- scales of odour intensity standards whose concentrations form geometric series can be consider linear scales;

Less clear is the answer to the question regarding determination of odorant concentration and threshold using the extrapolation toward $I = 0$. Figure 5 and 6 represent rough comparison of determined functions $I = k \cdot \log_{10}(C/C_0)$ and $I = a \cdot (C - C_0)^n$ for the

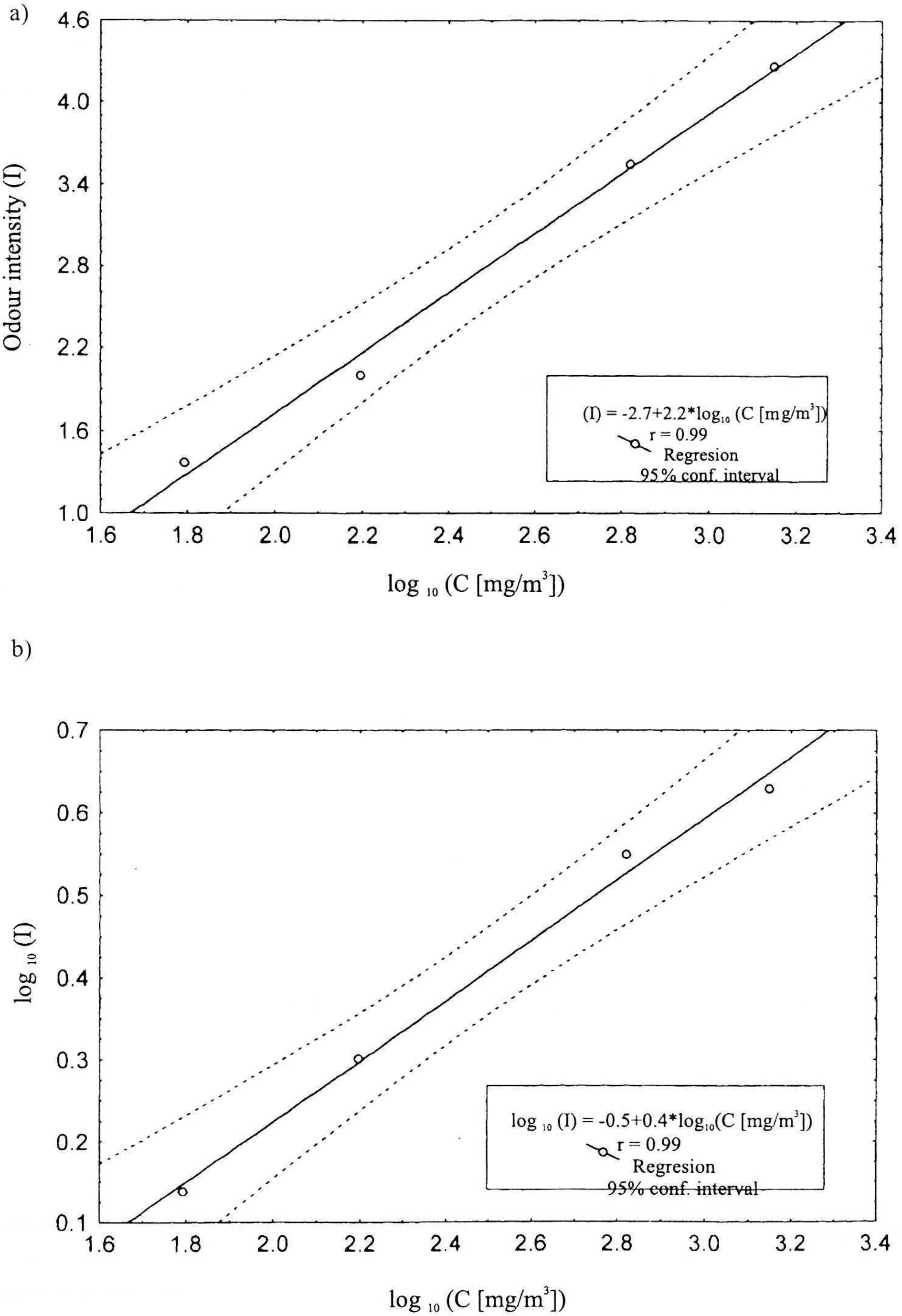

Fig. 3. Correlation between: (a) odour intensity (*I*) and logarithm of acetic acid concentration (log_{10} *C*); (b) logarithm of odour intensity (log_{10} *I*) and logarithm of acetic acid concentration (log_{10} *C*)

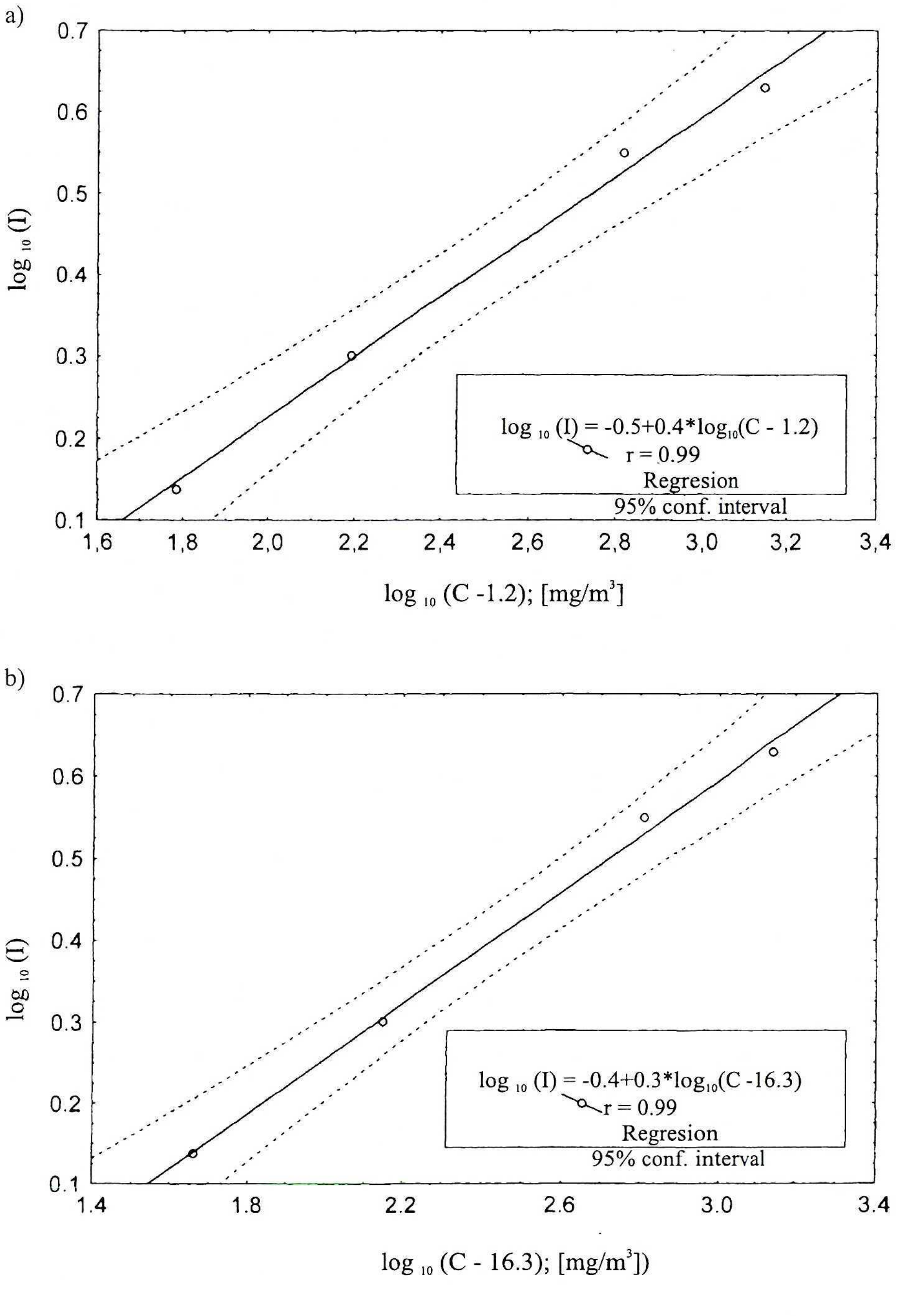

Fig. 4. Correlation between: (a) logarithm of odour intensity (*$log_{10} I$*) and logarithm of difference between acetic acid concentration and detection threshold taken from literature (*$log_{10} (C - 1.2)$*) [2]; (b) logarithm of odour intensity (*$log_{10} I$*) and logarithm of difference between acetic acid concentration and detection threshold calculated (*$log_{10} (C - 16.3)$*).

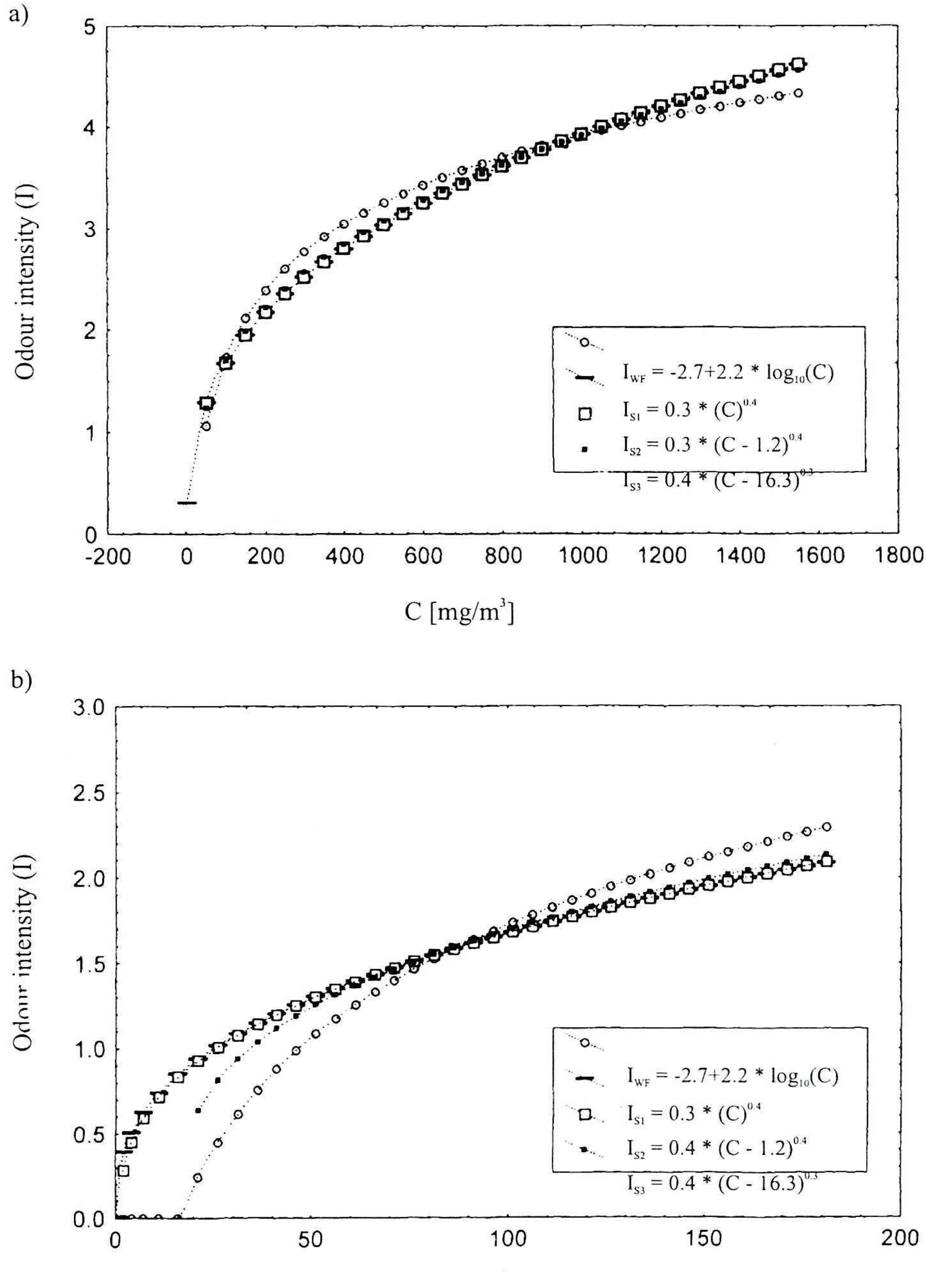

Fig. 5. Rough comparison of the determined functions $I = k \cdot log_{10}(C/C_0)$ (graph a) and $I = a \cdot (C - C_0)^n$ (graph b) for the entire range of acetic acid concentrations drawn in a coordinate system of odour intensity vs. acetic acid concentration. Different values of the threshold C_0 were used for calculations. Points on the chart represent results of calculations

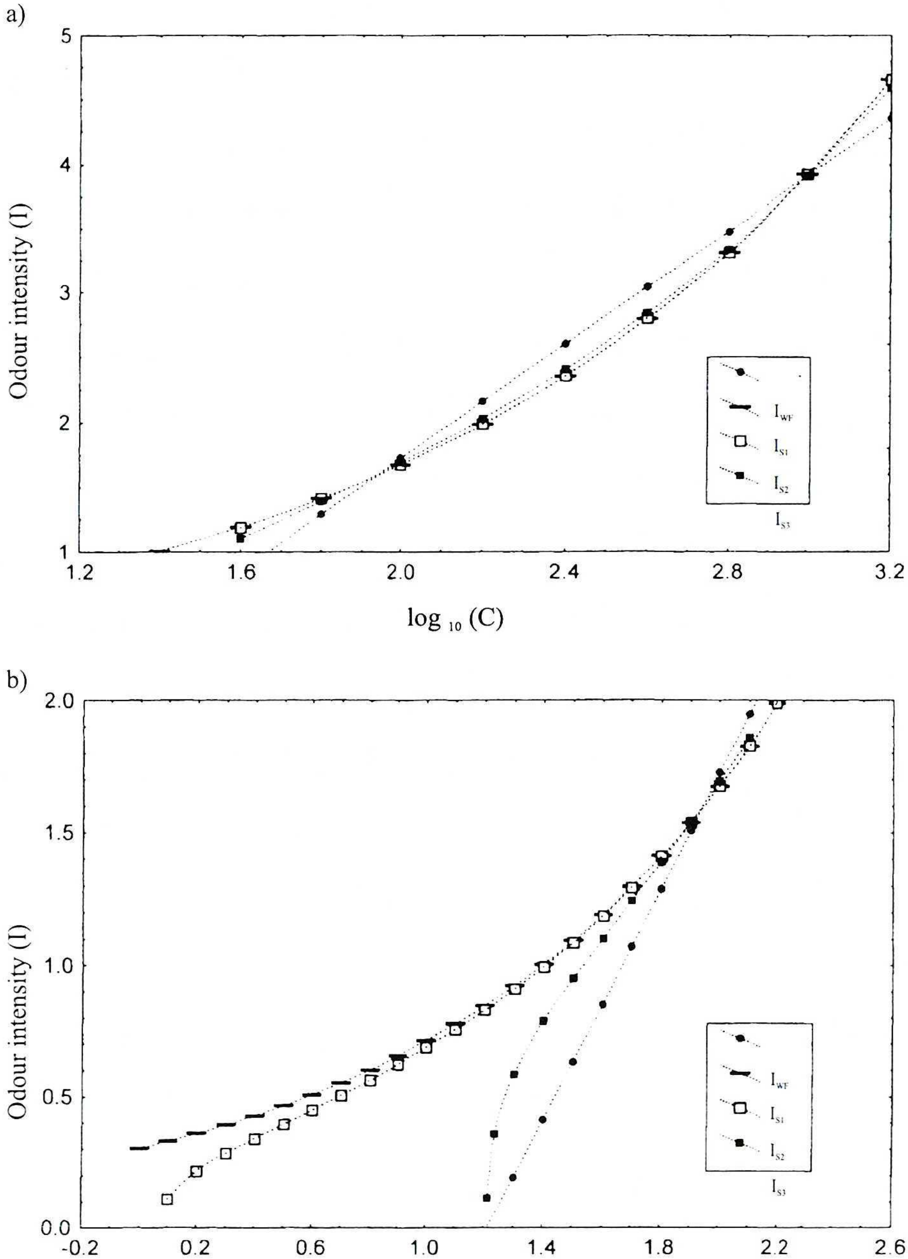

Fig. 6. Rough comparison of the determined functions $I = k \cdot log_{10}(C/C_0)$ (graph a) and $I = a \cdot (C - C_0)^n$ (graph b) for the entire range of acetic acid concentrations redrawn in a coordinate system of odour intensity vs. logarithm of acetic acid concentration. Different values of the threshold C_0 were used for calculations. Points on the chart represent results of calculations

entire range of concentrations and with different assumptions regarding the threshold C_0. Both results of the odour intensity calculations are most consistent when the extrapolated value C_0 = 16.3 mg/m^3 was used. That proves the consistency of both equations for the range $I < 1.5$.

The fact that determined C_0 value is about ten times higher than the average literature value [2] needs explanation.

The value C_0 = 16.3 mg/m^3 is the threshold in presence of the various factors that make the perception difficult (additional olfactory, visual or acoustic sensations). The "environmental" threshold determined in those conditions is obviously higher than the "absolute" one – determined in standard, laboratory conditions. The "environmental" threshold value is very important from the standpoint of the environmental service – it gives information about the concentrations of pollutants that can cause noticeable worsening of the odour air quality.

CONCLUSIONS

1. The dependence of odour intensity against odorant concentration can be expressed using the logarithmic Weber-Fechner law or the Stevens' power law. The laws are equally fulfilled if experimental data is obtained using the same method (the same conditions and the same sensory measurement technique).
2. For the purpose of threshold determination the extrapolation toward the intensity $I = 0$ can be used.
3. The odour thresholds under "natural" conditions ("environmental" thresholds) can be about ten times higher than the absolute thresholds determined with standard methods.
4. It is advisable to continue the research using another odorants and more accurate methods of determination of the pollutant concentration in samples.

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