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Ionization Impact on the Air Cleaning Efficiency in the Interior

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The paper deals with ionization impact on efficient cleaning of air in a measuring chamber which has been cleaned and closed against any outer impacts (e.g. impurities, dust from another room, human odours). Smoking has an impact on the number of positive and negative ions including the concentration of particulate matter PM_{10}. We investigated the ion concentration according to the presence of cigarette smoke in the room and according to the change of lit cigarette distance from the supply of ionized air. Due to the experiment there was simulated smoking at the relative air humidity $\varphi = 37$ % and $\varphi = 39$ % and temperature of 20 °C in the room. Increased PM_{10} concentrations were caused only by cigarette smoke pollution or more precisely by artificially created higher humidity in the measuring room excluding ambient environment impacts. The aim of the experiments was to prove influence of ionization on the elimination of cigarette smoke. The measurements showed that the highest efficiency of PM_{10} particulate removal was achieved when the distance of smoking cigarettes from ionization source was 3 m and the air humidity was 39 %. The consequent increase of the distance of smoking cigarettes from the ionization source significantly decreased the efficiency of particle removal. The difference between ionized and natural air is minimal at the bigger distance.

Keywords: Ionization, particular matters, cigarette smoke, particle removal efficiency, positive and negative ions.

1. INTRODUCTION

MODERN BUILDINGS should provide their users with satisfactory conditions for their comfort and health. Currently, a great emphasis is placed on maintaining interior thermal and humidity conditions to ensure the comfort of a particular interior through economic, energetic, and ecologic operation. However, the phenomenon referred to as sick building syndrome [1] is observed in many buildings even if optimal thermal and humidity conditions are maintained. Sick building syndrome was originally described by [2].

People suffer various subjective sorts of discomfort such as headache, insomnia, fatigue, nervousness, joint aches, high blood pressure, which decrease work productivity. It has been recognised that these discomforts appear when there is a higher number of positive ions in the air where the person is [3]. The positive ions prevail in industrial areas and densely populated places (housing estates, busy downtown sections, etc.) and enclosed rooms, which means in the places where we spend most of our lives. One of the causes is presented especially by artificial materials which surround us (PVC flooring, synthetic carpets, and plastic windows), modern appliances (printers, copy machines, fluorescent lamps, TV sets, LD monitors, mobile phones), chemical cleaning agents, polluted air and cigarette smoke. The worst "enemy" of ionization is air conditioning which creates un-natural, artificial environment destroying natural microclimate by destroying all negative ions [4].

Negative ions have positive effects on humans and they are said to be air vitamins. Their presence is highest especially in the nature after a storm, in caves, in the forest, near waterfalls, at a sea coast, etc. Negative ions are a significant and important source of energy for a human body. They support the immune system and mental well-being. Thanks to them we feel happy, relaxed and we can breathe easy. This results in good mood, better work productivity, and peaceful sleep [4].

As the favourable impact of light negative ions on man and their body has been proved, there is an effort to ensure such an environment where the concentration of negative ions in the living space approaches the maximum of their concentration in the natural, unpolluted environment. This aim can be achieved by building our dwellings from suitable natural materials or by modification of our existing dwellings and work spaces [3].

Negative ions can enter the interior from the exterior or can be produced by an ionizing appliance in the interior. Ion generators, or ionizers, have been constructed for this purpose [5].

Ionization has been used to clean the air in an internal environment by reducing dust particles and aerosols from volatile organic substances [6], [7]. Ions also have antibacterial effects and may decrease the amount of microorganisms and allergens in the air [8]. [9] investigated negative ion concentrations at various room humidity levels and at various distances from the ionization source. The ion life cycle was approximately 100 s. The undesirable effects related to air ionization include excessive electrostatic discharge and charge of objects, dust accumulation on surfaces in a room resulting in the need of regular cleaning [10]. Another side effect of the ionization process is ozone (O_3) emissions [11]. Some advantages of the use of ionization compared to other methods of cleaning internal environments include its low energy costs, reduced

formation of dangerous emissions, and a number of potential health advantages described by [12].

[13] investigated the effectiveness of ionization in reducing the concentration of dust particles in a closed testing chamber at various distances from the ionization source [14]. [15] considered the impact of negative ions on aerosols, microbes, odours, and evaporating organic substances in an interior environment. [16] investigated the removal of aerosols from the air in an internal environment [17]. Research into the concentration of selected pollutants in the external and internal environment of buildings has been conducted by [18].

[19] examined air pollution from cigarette smoke in an internal environment. The study aimed to establish the concentration trends of polluting substances created by smoking in a controlled internal environment [20], [21].

[22] states that smoking is the greatest source of PM_{10}. $PM_{2,5}$ and PM_1, which negatively impact health, have also been discussed in recent studies [23]. [24] provided data on the concentrations of PM_{10}, PM_5, $PM_{2.5}$, and PM_1 measured in an interior and exterior of a primary school in India. Some publications [25], [26], [27] presented the measurement of the concentration of dust particles during cooking and attempted to eliminate such particles by ionization.

[28] presented an automatic device for a precise measurement of ion concentration in the atmosphere.

The aim of our experiments was to prove a positive impact of ionization on decreasing aerosol concentration, in particular, cigarette smoke in the interior of buildings.

Cigarette smoke is a source of chemical substances contaminating the environment. A number of chemical substances presents adverse health effects (genotoxicity, carcinogenicity, hormonal imbalance, etc.) Cigarette smoke products burden especially the interior of buildings, smokers' workplaces, restaurants, other public spaces, interiors of cars, etc.. Cigarette smoke negatively influences not only smokers themselves, but the people around as well. Therefore, it is important to remove it effectively.

Cigarette smoke contains solid particles belonging into $PM_{2,5}$ category, i.e. particles of the size smaller than 2.5 μm. Negative ions have an ability to tie these solid particles and form clusters out of them. This contributes to faster sedimentation or increases the efficiency of filters and in such way contributes to the elimination of cigarette smoke in interiors.

2. IONIZATION

The atmosphere surrounding us is constantly ionized. The sources of the ionization energy affect the Earth continuously and, therefore, electrically neutral air does not practically exist. The source of energy activating ionization of air is electromagnetic radiation (space radiation, solar ultraviolet radiation, and gamma radiation of radioactive materials) [29].

We encounter ions practically all the time and everywhere, because they are an inseparable part of the atmosphere which surrounds us everywhere. In the air there are ions of two polarities, that is the positive one – cations and the negative one – anions. The way they influence us depends on their mutual ratio.

At the end of the nineteenth and the beginning of the twentieth century many physicists discovered that independent discharging of the charged electroscope is caused by conductive particles – ions in the air atmosphere. Gas molecules are electrically neutral in normal conditions. A certain amount of energy is needed for air ionization to occur [30]. This minimum amount of energy is identified as ionization energy. When the ionization energy is reached, non-elastic collisions of formerly neutral particles occur. These collisions cause one or more electrons to separate from the orbital atom course, thus forming pairs of electrically charged particles. These electrically charged particles carry a negative charge, and the remaining atoms carry a positive charge [31]. Therefore, in natural ionization a pair of electrically charged particles, with each particle having the opposite charge, is always formed.

The particles that are formed are not stable, and they connect with neutral charges or molecules, forming a complex of up to 30 molecules; these molecules are reasonably stable and are called light positive and negative ions. The process of light positive and negative ion formation occurs in a fraction of a second. The scheme of ion particle formation is illustrated in Fig.1.

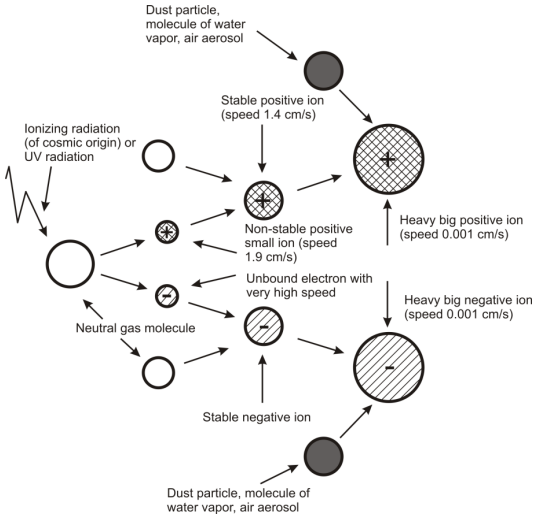

Fig.1. The principle of ion particle formation in the atmosphere.

The amount of ions found in the nature is always subjected to the condition of neutrality [32]:

$$\sum_i n_i z_i = 0 \,, \tag{1}$$

where n is the number of charges and z is the charge number.

Charged particles have different features than neutral particles, and the presence of charge can significantly influence the behaviour of substances in which they are found [33]. Based on the condition of neutrality (1), the natural concentration of positive and negative ions is balanced. We can refer to ions in the air as an example of this balance [34].

Air cleanliness is defined according to ion concentrations using the coefficient of unipolarity defined for light and heavy ions (UQ_1 and UQ_2, respectively):

$$UQ_1 = \frac{n_+}{n_-} \quad \text{and} \quad UQ_2 = \frac{N_+}{N_-}, \tag{2}$$

The unipolarity coefficient is a ratio of the number of positive (n+ for light ions, N+ for heavy ions) to negative ions (n– for light ions, N– for heavy ions). In the nature, the unipolarity coefficient is always higher than one. In the unpolluted atmosphere, the value ranges from 1.15 to 1.25. In severely polluted environments, such as in the proximity of large industrial plants, the unipolarity coefficient ranges from 4.0 to 6.0. The high prevalence of positive ions over negative ions is only relative because the unfavourable ratio of positive and negative ions is caused by the increased extinction of negative ions due to the impact of air pollution. Meanwhile, there are new ionization processes occurring [13].

The phenomenon of ionization is regularly accompanied by a series of chemical reactions. Two such reaction products are the formation of O_3 and nitrogen oxides [35]. It is necessary to emphasize that O_3 is a colourless gas with a characteristic odour which easily disintegrates and releases atomic oxygen [36]. Therefore, it has strong oxidation effects. It destroys a wide range of microorganisms, but inhalation at greater concentrations can lead to health risks [37].

Human beings also affect ion concentrations in internal environments through various activities. Smoking and humidity have significant impacts on the concentration of PM_{10}. The gross mass (M) of settled PM_{10} particles is normally measured through gravimetric method [38]. It can be determined with a TEOM apparatus [39]:

$$M = \frac{K_0}{f^2}, \tag{3}$$

where f is the frequency of the spring mass system of the TEOM measuring apparatus, the spring constant K_0 with mass recalculation factor is [40].

$$K_0 = \frac{dm}{\frac{1}{f_1^2 - f_0^2}}. \tag{4}$$

In equation (4), dm is the mass change, f_0 is the initial frequency of the vibrating system before dust falls on the changeable filter, and f_1 is the final frequency of the vibrating system after dust falls on the changeable filter.

The overall mass of settled particles is used to determine the difference between the particles' current gross mass and the mass of the particles caught in the filter.

3. Experimental measurements

Experimental measurements were performed in two rooms – a control room (CR) and a measuring room (MR).

A. Control room

The control room was completely isolated from the measuring room so that no influencing of results in the measuring room can occur while persons move in the control room.

The scheme of experimental device placement in the control room (CR) and the measurement room (MR) is shown in Fig.2.

The air-technical device consisted of a fan F1 (1), which blew air from the control room (CR) through air-technical pipes with the ionization device (DEZOSTER) (2) (provided by company HIVUS, s. r. o., Žilina, Slovakia) and a textile filter into the measuring room. The DEZOSTER contains ionizing tubes (ITs), which provide air ionization and create negative ions. Negative ions are created by an electrical discharge, similar to a storm principle. This method uses a "corona" that is formed by the creation of high voltage between two electrodes. The corona releases a large number of electrons, which create negative ions from the surrounding air molecules. The intensity of air ionization in the DEZOSTER could be adjusted by switching from the first to fourth position (Fig.2.). The switch position 0 turns the device off. By using the filter (F), particles were caught after being sucked in by the fan (F1) from the control room, thus preventing cigarette smoke from influencing measurements of particulate formation in the measuring room.

The control room contained a TEOM control unit (4) dust-measuring apparatus and a pump (3) to provide circulation of the air being sucked into the TEOM dust-measuring apparatus. The TEOM 1400a PM_{10} is a measurement device that works in real time and is designed to determine the concentration of volatile dust (particles) with a diameter less than 10 μm (PM_{10}). The principle consists of capturing the particles from the air sample on a filter made of glass fibres and covered with a layer of Teflon. This filter is weighed every 2 s. The difference between the current weight of the filter and the weight of the filter determined at the beginning of the measurement indicates the total weight of particles captured by the filter.

The data were recorded using an HDL-TRH-D/LP data logger. This device has a temperature measurement range from –20 to +70 °C (±0.9 °C) and a relative humidity range of 0–100 % (±0.5 %). The O_3 concentration in the measurement room was measured and recorded using an OZONE SENZOR OS-11 data logger. The ion concentration in ppm units is one of the outputs. The device is also equipped with a control button which starts to flash red when the limit ozone value is exceeded. This value is set to 0.05 ppm which is a limit stated by Regulation No. 259/2008 of Coll. of Laws as a hygiene standard for work environment. This device has a working dimension from 0–0.2 ppm. The precision of the measurements is 10–20 % in the range of 0.03–0.1 ppm. Using the data loggers, the data were uploaded to a computer through a USB port and evaluated.

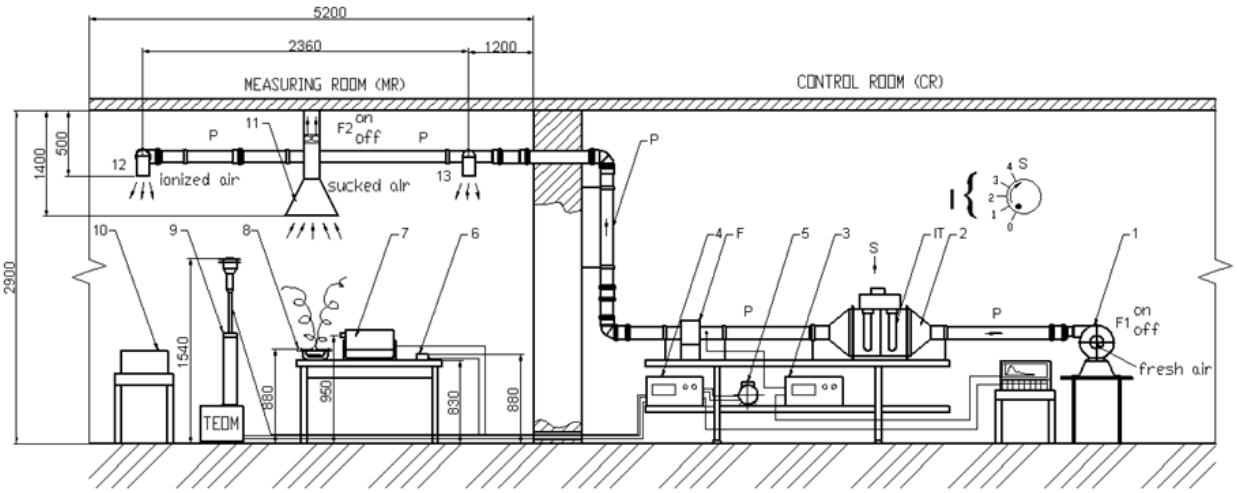

Fig.2. Diagram of the location of the experimental devices in the measuring room (MR) and the control room (CR)
1 – fan F1, 2 – air-technical piping with ionizer DEZOSTER, 3 – Ozone Analyzer, 4 – control unit of the TEOM 1400a dust-measuring apparatus, 5 – pump of the dust-measuring apparatus, 6 – sensor for measuring the humidity, temperature, and O3 concentration in the room, 7 – ion-measuring unit, Ion Counter IC 2000, 8 – cigarette smoke source, 9 –TEOM 1400a dust-measuring apparatus, 10 – humidifier Solac HU 1050, 11 – sucking device, 12, 13 – inlets for ionized air, F – textile filter, P – air-technical piping, IT – ionizing tubes.

B. Measuring room

The measuring room, in which the experiments took place, was on the ground floor. The outer walls were constructed from bricks. The room had tiled walls, a tiled floor, and a plastered ceiling. The room temperature was 20 °C (±1 °C) in all of the measuring tests. The room dimensions were 5200×4900×2900 mm (l×w×h). The distances of the air-technical elements from the ceiling and the location of the measuring devices, including the cigarette smoke inlet, are provided in Fig.2. The "smoke wire" method was used to visualize the air flow direction from the inlets in the measuring room; its principle has been described in the literature [41].

The measuring room contained the following: a TEOM (9) dust-measuring apparatus, which was used to measure PM_{10}; a Solac HU 1050 (10) humidifier, a sensor for measuring the humidity, temperature, and O_3 concentration in the room (6); and an Ion Counter IC 2000 (7), a device for measuring the amount of positive and negative ions. The ion counter is a continual measuring device with a measurement range of 0–2000 ions/cm^{-3}, with a precision of 20 ions/cm^{-3}. The Solac HU 1050 V is an air humidifier which is used to increase the relative humidity in a building's interior. Its water container has the capacity of 900 ml and allows operation of the device for up to 12 h. The Solac HU 1050 V uses ultraviolet (UV) technology to create humidity. Within the room, there was also an air-exhaust technical device (11), with the exhaust air flow speed of $v_2 = 0.6$ m/s^{-1}. The exhaust device in the measuring room was used mainly for forced ventilation, and it accelerated the time required to clean the measuring room's interior environment of various aerosols.

The measuring room contained air-technical piping P, for the ionized air inlet from the control room. The ionized air supply was provided by two inlets (12, 13) located under the measuring room ceiling. The O_3 concentration in the tube from the DEZOSTER was recorded using the Ozone Analyzer Model 8810. The analyser continuously measures the O_3 concentration in an air sample by measuring the UV radiation absorbed by the air. The device has a detection limit of 1 ppb and is able to monitor the concentration of O_3 in the air in the range 0.0–10.0 ppm.

C. Measurement of the ion concentration, PM_{10} and O_3 ozone

During the experiments we investigated the concentration of PM_{10} ions and ozone O_3 for lit cigarettes depending on relative air humidity in the measuring room. Meanwhile, we were observing the behaviour of negative ion level under a long-term impact of ionization.

Gross impurities and dust had been removed from the measuring room before the measurements were done. Air ionization was carried out for two days to stabilize the environment and because of the chemical composition properties of internal surfaces of the interior, i.e. surface saturation by O_3. Before each measurement the marginal conditions were measured to ensure the relative humidity (RH) of 37−39 % and the temperature of 20 °C. Then, the devices were prepared for the measurements.

Before every measurement the measuring room was ventilated and all impurities from the previous measurements were removed trough an exhaust pipe. Next, the room was closed and exposed to the ionization process in order to create negative ions in the room.

Four cigarettes were placed on the table in the room (see Fig.2.) and were lit after the fan F1, the exhaust F2, and the measuring devices (TEOM, Ion Counter, Ozone Analyzer) had been turned on. A detailed review of the measured values and the initial conditions for measuring are provided in Table 1.

Table 1. Summary of the measured values.

Measured values	Devices + testing element	on/off	Value/magnitude being measured	Period of ON status since the beginning of the measurements t [in min]	Values in the measuring room at the beginning of the measurements
Measurement No. 1					
v_1	Fan (F1)	On	4.04 $m.s^{-1}$	150	t = 20 °C
v_2	Fan (F2)	On	0.6 $m.s^{-1}$	150	φ = 37 %
O_3	Ionizer	off	0.001 ppm	0	O_3 = 0.001 ppm
φ	Solac HU	on	39 %	150	PM_{10} = 5 $\mu g.m^{-3}$
PM_{10}	TEOM	on	8.2 $\mu g.m^{-3}$	150	i+ = 210 $ions.cm^{-3}$
neg. ions pos. ions	Ion Counter	on	312* $ions.cm^{-3}$ 218* $ions.cm^{-3}$	150	i– = 230 $ions.cm^{-3}$
Measurement No. 2					
v_1	Fan (F1)	on	4.04 $m.s^{-1}$	150	t = 20 °C
v_2	Fan (F2)	on	0.6 $m.s^{-1}$	150	φ = 37 %
O_3	Ionizer	on	1.5 ppm	150	O_3 = 0.001 ppm
φ	Solac HU	on	39 %	150	PM_{10} = 5 $\mu g.m^{-3}$
PM_{10}	TEOM	on	10.3 $\mu g.m^{-3}$	150	i+ = 240 $ions.cm^{-3}$
neg. ions pos. ions	Ion Counter	on	165* $ions.cm^{-3}$ 188* $ions.cm^{-3}$	150	i– = 120 $ions.cm^{-3}$
Measurement No. 3					
v_1	Fan (F1)	on	4.04 $m.s^{-1}$	150	t = 20 °C
v_2	Fan (F2)	on	0.6 $m.s^{-1}$	150	φ = 37 %
O_3	Ionizer	off	0.001 ppm	0	O_3 = 0.001 ppm
φ	Solac HU	off	37 %	0	PM_{10} = 5 $\mu g.m^{-3}$
PM_{10}	TEOM	on	7.4 $\mu g.m^{-3}$	150	i+ = 170 $ions.cm^{-3}$
neg. ions pos. ions	Ion Counter	on	53* $ions.cm^{-3}$ 63* $ions.cm^{-3}$	150	i– = 200 $ions.cm^{-3}$
Measurement No. 4					
v_1	Fan (F1)	on	4.04 $m.s^{-1}$	150	t = 20 °C
v_2	Fan (F2)	on	0.6 $m.s^{-1}$	150	φ = 37 %
O_3	Ionizer	on	1.5 ppm	150	O_3 = 0.001 ppm
φ	Solac HU	off	37 %	0	PM_{10} = 5 $\mu g.m^{-3}$
PM_{10}	TEOM	on	8.5 $\mu g.m^{-3}$	150	i+ = 160 $ions.cm^{-3}$
neg. ions pos. ions	Ion Counter	on	45* $ions.cm^{-3}$ 52* $ions.cm^{-3}$	150	i– = 60 $ions.cm^{-3}$

*averaged over 150 min

3. RESULTS

A. Influence of ionization on the PM_{10} concentration and number of negative and positive ions

Measuring tests were performed with the humidity values of 37 and 39 % to determine the PM_{10} concentration and the amount of negative and positive ions in the measuring room (Fig.2.) resulting from the cigarette smoke. As a cigarette smoke source, four cigarettes (cigarette length was 80 mm) were allowed to passively burn, and their burning period was approximately 15 min. The composition of the most significant harmful substances during the burning process of one cigarette is: tar – 10 mg/cigarette, nicotine – 0.7 mg/cigarette, O_2 – 10 mg/cigarette.

Tobacco smoke is a complex of more than 4000 gaseous (92 %) and solid (8 %) substances and contains approximately 64 carcinogens, including dibenzanthracene, benzo[a]pyrene, mutagens, allergens, and other toxic substances. The smoke contains a large amount of carbon monoxide (5–10 %) and approximately 700 additives. [42] have described selected constituents of cigarette smoke in detail.

The following measuring tests were performed by measuring sensors (ion concentration sensor, dust particle

sensor, ion sensor) and the source of cigarette smoke (lit cigarettes) at a distance of 3 m from the inlets through which the ionized air flowed into the measuring room. The marginal conditions prior to the first measurement were as follows: $PM_{10} = 5$ µg/m^3, $O_3 = 0.001$ ppm, positive ions = 210 ions/cm^{-3}, and negative ions = 230 ions/cm^{-3}. During the first measuring period, the humidifier was also turned on, and humidity was increased from 37 % to 39 %. During this measurement, in addition to the PM_{10} concentration, the numbers of positive and negative ions were monitored; the DEZOSTER ionizer was turned off, and the O_3 concentration in the air-technical piping was 0.001 ppm.

Fig.3. presents the increasing concentration of PM_{10}, which rapidly increased to a maximum value of 240 µg/m^3. The PM_{10} concentration decreased when the burning process was over. The amount of negative ions increased from 240 to 400 ions/cm^3 during the cigarette burning. When the burning process was over, the amount of negative ions decreased to 280 ions/cm^3. The amount of positive ions increased from 200 to 250 ions/cm^3.

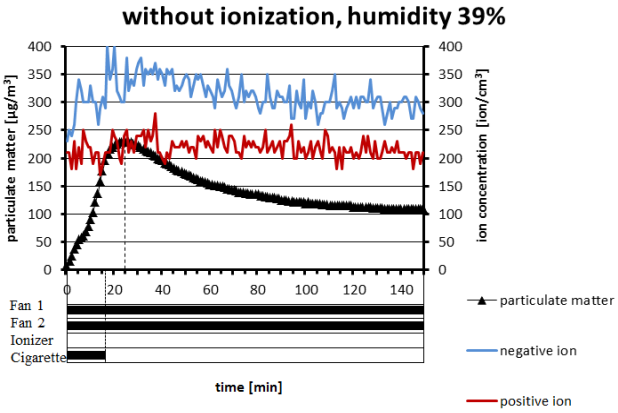

Fig.3. Measurement graph No. 1 for dust particles PM_{10} and number of negative and positive ions (without ionization, humidity = 39 %, distance of lit cigarettes from ionized air inlet 3 m).

After settling the environment after the first measurement, the devices were prepared for the second measurement. The marginal conditions prior to the second measurement were as follows: $PM_{10} = 5$ µg/m^3, $O_3 = 0.001$ ppm, positive ions = 240 ions/cm^3, and negative ions = 120 ions/cm^3. In this case, ionization was initiated at level four. Ionized air was introduced into the measuring room by air-technical piping and the F1 fan (on). Ionized air was introduced from the control room through the filter, which is a part of the air-technical piping, up to the measuring room, where it was led through inlets. During this measuring period (Fig.4.), the PM_{10} concentration increased to a maximum of 360 µg/m^3.

The ionization room-cleaning process significantly influenced the amount of ions. Negative ions tended to decrease and ranged from 140 to 200 ions/cm^3. The amount of positive ions decreased to less than 200 ions/cm^3. The O_3 concentration of 0.258 ppm was measured in the air-conditioning tube. The O_3 concentration in the room reached 0.114 ppm.

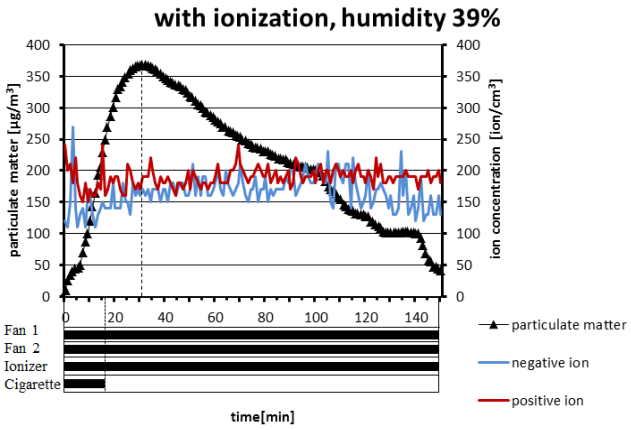

Fig.4. Measurement graph No. 2 for dust particles PM_{10} and number of negative and positive ions (with ionization, humidity = 39 %, distance of lit cigarettes from ionized air inlet 3 m).

In the third measurement, the humidity was 37 % and the room temperature remained at 20 °C. The marginal conditions prior to the third measurement were as follows: $PM_{10} = 5$ µg/m^3, $O_3 = 0.001$ ppm, positive ions = 170 ions/cm^3 and negative ions = 200 ions/cm^3. In this measurement, air cleaning ionization was turned off again, and air flow was forced into the room by the F1 fan (off). As shown in Fig.5., the PM_{10} concentration increased during the application of cigarette smoke to the maximum of 190 µg/m^3. The concentration of negative ion values tended to decrease due to the decreased humidity, reaching the concentration of 50–90 ions/cm^3. The concentration of positive ions tended to increase, reaching the final concentration of 50 to 150 ions/cm^3. The DEZOSTER was off, and the concentration of O_3 in the tube and in the room was 0.001 ppm.

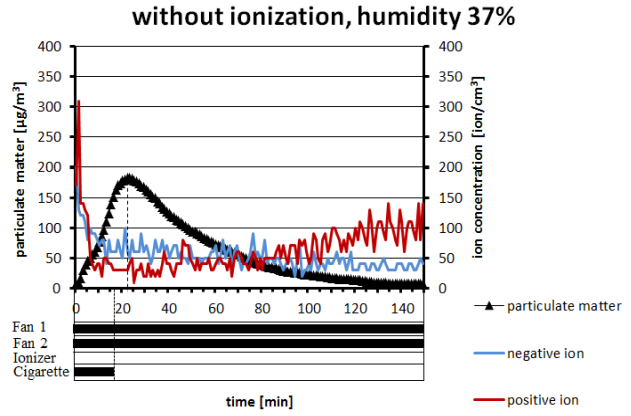

Fig.5. Measurement graph No. 3 for dust particles PM_{10} and number of negative and positive ions (without ionization, humidity = 37 %, distance of lit cigarettes from ionized air inlet 3 m).

In the last measurement (Fig.6.), with the humidity of 37 % and the room temperature of 20 °C, air ionization was turned on to level four and the F1 fan was on. The marginal conditions prior to the fourth measurement were as

follows: $PM_{10} = 5$ µg/m^3, $O_3 = 0.001$ ppm, positive ions = 160 ions/cm^3, and negative ions = 60 ions/cm^3. The PM_{10} concentration increased above 250 µg/m^3, which is greater than the results in the measurement No. 3, due to the forced air flow and the increased O_3 concentration in the measuring room. Due to ionization, the negative ions decreased to 50 ions/cm^3, whereas the positive ions increased to over 50 ions/cm^3. The concentration of O_3 was 0.245 ppm, and the O_3 concentration in the room was 0.130 ppm.

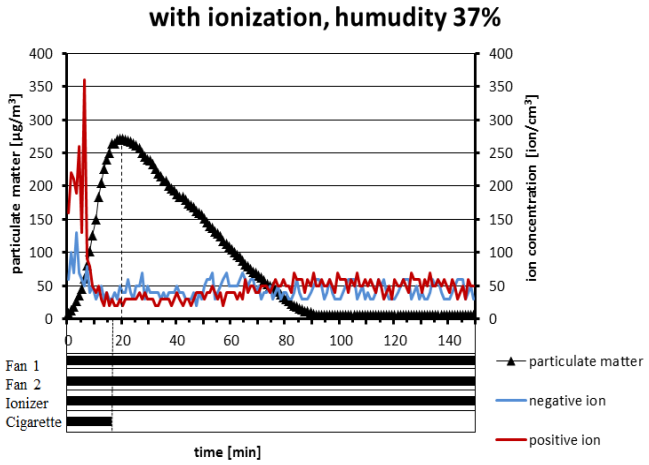

Fig.6. Measurement graph No. 4 for dust particles PM_{10} and number of negative and positive ions (with ionization, humidity = 37 %, distance of lit cigarettes from ionized air inlet 3 m).

B. Influence of distance of smoking cigarettes from ionization source on the PM_{10} concentration

To verify the impact of distance of sensor (ion counter, dust sensor) and the cigarette smoke source from the ionization source on the particle removal efficiency a series of measurement tests was performed. The measurement tests were repeated at the same marginal conditions (humidity levels of 37 % and 39 %, temperature of 20 ºC) as the above-described measurement tests while only the distance of measuring sensors and cigarette smoke source was changed from the ionized air supply inlets. The marginal conditions were as follows: $PM_{10} = 5$ µg m^{-3} and $O_3 = 0.001$ ppm. The distances of the sensors and smoking cigarettes from the air supply inlets were 3.5, 4, and 4.5 m, and their arrangement is illustrated in Fig.7.

The measurement test results, where only distances of measuring sensors and the cigarette smoke source from the ionization source were altered, are graphically illustrated in Figs.8-10. Fig.8. illustrates that the PM_{10} concentration without ionization is the highest when cigarettes have been burning for approximately 10 min, after which it decreases slightly. Minimal differences were observed for the distances of 4 and 4.5 m, and the values are between 300 and 500 µg/m^3 for the 150 min period. A slight decrease in the PM_{10} concentration occurred at a distance of 3.5 m after 15 min. The impact of the exhaust device located under the ceiling in the middle of the measuring room is evident; the device is also located above the smoke source and the PM_{10} and O_3 sensors.

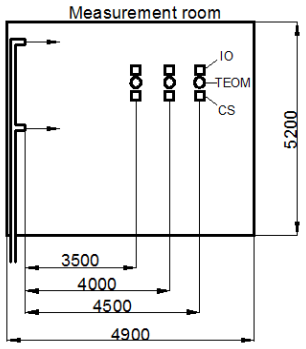

Fig.7. Location of the sensors and cigarette smoke source in the measuring room from ionization source (values in mm) IO – ion counter, TEOM – dust measuring apparatus, CS – cigarette smoke.

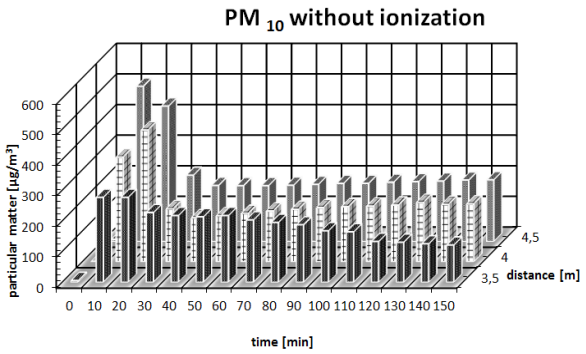

Fig.8. PM_{10} concentration according to the distance of smoking cigarettes from the ionization source (without ionization, humidity = 37 %).

Fig.9. presents the dependence of the PM_{10} concentration on time, with ionization on, at distances of 3.5, 4, and 4.5 m and at the humidity of 37 %. The PM_{10} concentration at the distance of 3.5 m quickly decreased after burning of cigarettes had finished and after 150 min it was 9.8 µg/m^3. At distances of 4 and 4.5 m, the ionization impact on the concentration was markedly smaller after 30 min than at the distance of 3 m, reaching values of approximately 130–140 µg.m^{-3}.

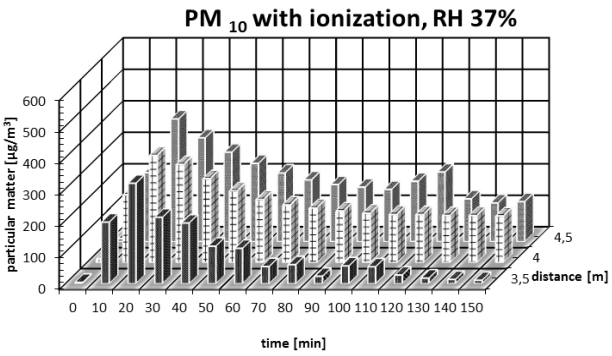

Fig.9. PM_{10} concentration according to the distance of smoking cigarettes from the ionization source (with ionization, humidity = 37 %).

Fig.10. presents the dependence of the PM_{10} concentration on time, with ionization on, at distances of 3.5, 4, and 4.5 m and at a humidity of 39 %. The PM_{10} concentration values at all distances steadily decreased after 15 min, and they were within the interval of 360 to 150 µg/m^3 after 150 min. The measuring tests indicated that the distance had a minimal impact on the PM_{10} concentration even with the 2 % increase in humidity.

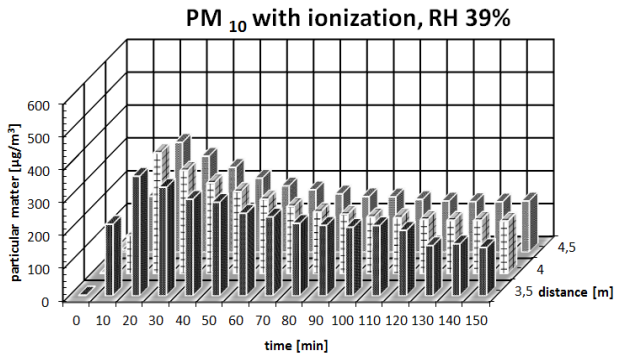

Fig.10. PM_{10} concentration according to the distance of smoking cigarettes from the ionization source (with ionization, humidity = 39 %).

C. Efficiency of particulate matter removal and the air cleaning factor

The efficiency of particle removal was calculated according to the relation as follows [43]:

$$\eta = \frac{C(d_p, t=0) - C(d_p, t)}{C(d_p, t=0)}, \tag{5}$$

where $C(d_p, t=0)$ is the size-specific particulate matter concentration at time $(t=0)$, and $C(d_p, t)$ is the size-specific particulate matter concentration at time *t*.

The calculated particle removal efficiency is shown in Fig.11., where the data for distances of smoking cigarettes of 3 and 4.5 m from the ionization source with and without ionization in the room at the humidity of 39 % was compared. At the beginning of the measurement tests, when the cigarettes were lit, the particle removal efficiency at all distances rapidly decreased during the cigarette burning period (i.e. to 15 min). Immediately after the cigarettes finished burning, the particle removal efficiency decreased to below 10 %. In case of efficiency of particle removal by ionization at a distance of 3 m, a gradual increase in the particle removal efficiency occurred, which then continued until 110 min. After 140 minutes intensive cleaning occurred and the PM_{10} concentration returned to its initial value before the pollution. Without ionization (at distances of 3 and 4.5 m) and with ionization at a distance of 4.5 m, the particle removal efficiency during cigarette burning also decreased to below 10 %; however, the efficiency after approximately 15 min grew very slowly from 10 to 20 % until the end of the measuring period (165 min). The particle removal efficiency by natural methods at distances of 3 and 4.5 m and with ionization at 4.5 m was several times lower compared to the efficiency with ionization and with sensors located at 3 m.

The low particle removal efficiency at the farthest point (4.5 m) at the start of measuring was caused by an increase in the formation of medium and heavy ions, formed by the interaction with polluting aerosols. Sedimentation was accelerated due to the higher mass of the ions as recorded by the TEOM dust-measuring apparatus. The formation of medium and heavy ions diminished after the cigarettes stopped burning causing an increase in the particulate matter removal efficiency because new aerosol particles were no longer being formed and there was no air pollution source acting in the measuring room.

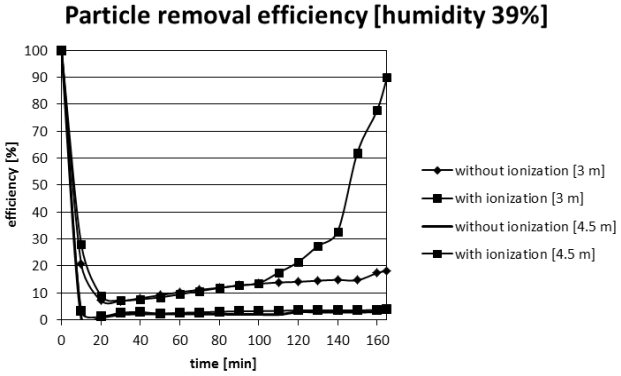

Fig.11. Particle removal efficiency.

The air cleaning factor (ACF) is defined as the ratio of the particulate matter concentration measured during the natural air cleaning time *t* to the concentration measured during air cleaning with ionization usage [44]:

$$ACF = \frac{C_{natural}(d_p, t)}{C_{ionizer}(d_p, t)}. \tag{6}$$

The ACF was determined according to equation (6), and the resulting values are listed in Table 2. The values listed in the table are calculated for times from 10 min, at the measuring start, to 150 min, when measurements were finalized. The results listed in Table 2. were recorded after every 20 min, with humidity values of 37 % and 39 %. The ACF at a humidity of 37 % was higher after 90 and 130 min due to more effective cleaning of particulate matter from the air by ionization. The values were lower after 130 min of cleaning because the particulate matter concentration in the measuring room was markedly lower; the cleaning and ionization at such a small concentration had a minimum influence on the cleaning efficiency.

Table 2. Air cleaning factor.

Air cleaning factor (ACF)								
Time (in min)	10	30	50	70	90	110	130	150
Humidity of 37 %	0.53	0.69	0.61	0.81	**2.97**	**2.7**	**1.49**	**1.23**
Humidity of 39 %	0.78	0.61	0.53	0.56	0.59	0.73	1.09	**2.43**

D. Comparison of the measured PM_{10} concentrations and the recommended limits

The experimental measurements indicated that the average PM_{10} concentrations exceeded the limit of 500 $\mu g.m^{-3}$ (Fig.9.). This measured concentration is many times higher than the maximum allowed 8 h values recommended by the National Ambient Air Quality Standards [45], (120 $\mu g.m^{-3}$), and the World Health Organization [46] (50 $\mu g.m^{-3}$). Other state limits are given in Table 3. This high PM_{10} concentration is due to the presence of cigarette smoke in the measuring room. Thus, we came to the finding that such a polluted measuring room is not suitable as a work environment in a building interior.

It should not be forgotten that ozone together with negative ions is also created in air ionizators which, on one hand, disinfects and kills microorganisms, but on the other hand, in an increased amount it affects people adversely. Ozone is stated as a harmful factor in the interior of buildings when its concentration exceeds 0.05 ppm according to Regulation No. 259/2008 of Coll. Therefore, it is necessary to set the level of ionization so that the produced ozone is under this level.

By the course of the regulation of the World Health Organisation (WHO) regarding the ozone effects on the environment and human health, the negative effect of ionization can be seen on the extra sensitive group of people even for the ozone concentration of 0.03 ppm. International regulation 2002/3/ES declares long-term objectives, target values, warning and informative threshold values for ozone concentration in the air. The measured values of O_3 at experimental measurements (150 min) reached 0.275 ppm. These values are in accordance with the stated limits of certain national organisations for a given period of time. Examples of maximal values of ozone concentrations in the indoor environment allowed by national organisations are in Table 4.

Table 3. National regulations, limits and requirements on indoor air quality (Max. Limits).

National organization/Country	Time (in hour)	Particulate matter PM_{10} (in $\mu g/m^3$)
Value measured by us	150 min	500
WHO	24	50
NAAQS	24	120
Finland	24	50
Lithuania	24	50
Portugal	24	150
Slovenia	24	100
France	24	50
Illinois	24	150
Hong Kong	24	180

Table 4. Stated ozone concentrations (Max. Limits) in the interior according to world organizations.

National organization	Time (in hour/min)	Concentration (in ppm)
Value measured by us	150 min	0.275
The Food and Drug Administration (FDA)	8	0.05
The Occupational Safety and Health Administration (OSHA)	8	0.1
The National Institute of Occupational Safety and Health (NIOSH)	8	0.1
Environmental Protection Agency´s (EPA´s)	8	0.08
Indoor Air Quality Association (IAQA)	8	0.05
World Health Organization (WHO)	8	0.05
American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE)	8	0.05
The Swedish National Board of Occupational Safety and Health:		
Level limit value (LLV)	8	0.1
Ceiling limit value (CLV)	15 min	0.3
Air Resources Board (ABR)	1 8	0.09 0.07

4. CONCLUSIONS

Indoor environment where people spend most of their time does not achieve such parameters of ion presence as it is in the nature environment which is natural for people. Aerosols, such as cigarette smoke, lead to decreasing the amount of negative air ions to almost zero. Therefore, it is necessary to supply the negative ions for healthier and more natural environment. Currently, there are many apparatuses which are able to produce negative ions artificially. A few years ago these apparatuses were designed solely for industrial use, however, now these devices are available also for households.

The measurements obtained in this study suggest that air cleanliness is closely related to the amount of negative and positive ions and the PM_{10} concentration. To achieve optimal conditions in building interiors, the environment must be clean and dust-free, and a sufficient amount of fresh air must be provided in the measuring room. The amount of negative ions significantly decreases due to the presence of cigarette smoke. However, in case of an increase of relative humidity the number of negative ions on the contrary increased.

All the experimental measurements focused on decreasing aerosols, in particular, cigarette smoke, in the interior. The used methods came from the assumption that negatively charged ions are able to bind solid particulates of cigarette smoke which are charged positively. This method can be used to find out indirectly how ionization influences the elimination of aerosols in the environment.

Experimental measurements were aimed at investigating the influence of humidity on aerosol elimination and all along on a long-term ionization influence on the room contaminated by cigarette smoke. We also observed the influence of the distance of smoking cigarettes from the ionization source on the amount of dust particles and ions in the room.

The analyses result in the fact that a remarkable influence of ionization appears around the ionization source where the PM_{10} concentration is higher. The increase of PM_{10} during the simultaneous influence of increased humidity and ionization is caused by heavy ions formed at the interaction of light ions and cigarette smoke and mist. The heavy ions settle down faster under the heavy weight which showed at an increase of dust particles PM_{10} measured by the dust-measuring device TEOM.

At bigger distances the ionization influence on PM_{10} concentrations is minimal.

The influence of humidity on PM_{10} concentration also takes place; in a shorter distance from the ionization source at the increased humidity the PM_{10} concentration is higher. At the lower humidity the PM_{10} concertation also decreased. The increased humidity in the bigger distance from the ionization source demonstrates minimal influence.

It is possible to state upon the experimental measuring that if ionization is used correctly and in a controlled manner in the interiors, it can remarkably contribute to healthier and more natural environment for people, with no negative impacts.

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REFERENCES

[1] Mackensen, S., Bullinger, M., Morfeld, M. (1999). The Sick Building Syndrome as a subjective perception-theoretical approach and assessment methods. *Zentralblatt fur Hygiene und Umweltmedizin*, 202 (2-4), 243-248.

[2] Wyon, D.P. (1992). Sick buildings and the experimental approach. *Environmental Technology*, 13 (4), 313-322.

[3] Polášková, A. et al. (2011). *The Introduction into the Ecology and the Environment Protection*. Charles University in Prague, 284 p. [in Czech]

[4] Högner s.r.o. (2005). *Air ionization*. http://cisticky-vzduchu.sk/ionizacia-vzduchu.htm. [in Slovak]

[5] Jakober, C., Philips, T. (2008). *Evaluation of Ozone Emissions From Portable Indoor Air Cleaners. Electrostatic Precipitators and Ionizers*. Staff Technical Report. California Environmental Protection Agency, Air Resources Board, 33 p.

[6] Daniels, S.L. (2007). On the qualities of the air as affected by radiant energies (photocatalyt ionization processes for remediation of indoor environments). *Environmental Engineering Science*, 6 (3), 329-342.

[7] Wu, C.C., Lee, G.W.M. (2004). Oxidation of volatile organic compounds by negative air ions. *Atmospheric Environment*, 38 (37), 6287-6295.

[8] Goodman, N., Hughes, J.F. (2004). The effect of corona discharge on dust mite and cat allergens. *Journal of Electrostatics*, 60 (1), 69-91.

[9] Parts, T-E., Luts, A. (2004). Observed and simulated effects of certain pollutants on small air ion spectra: I. Positive ions. *Atmospheric Environment*, 38 (9), 1283-1289.

[10] Tanaka, A., Zhang, Y. (1996). Dust settling efficiency and electrostatic effect of a negative ionization system. *Journal of Agricultural Safety and Health*, 2 (1), 39-47.

[11] Britigan, N., Alschawa, A., Nizkorodov, S.A. (2006). Quantification of ozone levels in indoor environments generated by ionization and ozonelysis air purifiers. *Journal of the Air & Waste Management Association*, 56 (5), 601-610.

[12] Daniels, S.L. (2001). Applications of air ionization for control of VOCs and PMx. In *94th Air and Waste Management Association Annual Conference*, Orlando, Florida.

[13] Shiue, A., Hu, S.-C., Tu, M.-L. (2011). Particles removal by negative ionic air purifier in cleanroom. *Aerosol and Air Quality Research*, 11, 179-186.

[14] Waring, M.S., Siegel, J.A. (2011). Indoor air quality implications of using ion generators in residences. *Indoor Air*, 21 (3), 267-276.

[15] Daniels, S.L. (2002). On the ionization of air for removal of noxious effluvia. *IEEE Transactions on Plasma Science*, 30 (4), 1471-1481.

[16] Grabarczyk, Z. (2001). Effectiveness of indoor air cleaning with corona ionizers. *Journal of Electrostatics*, 51-52, 278-283.

[17] Rexfort, C. (2004). *A Contribution to Fire Detection Modelling and Simulation.* Dissertation. University of Duisburg-Essen, 88 p.

[18] Monn, C., Schaeppi, G. (1993). Concentration of total suspended particles and fine particles and their anionic compounds in ambient air and in indoor air. *Environmental Technology*, 14 (9), 869-875.

[19] Christoforos, H.H., Assimakopoulos, V.D, Helmis, C.G., Flocas, H.A. (2005). Investigating cigarette-smoke indoor pollution in a controlled environment. *Science of The Total Environment*, 337 (1-3), 183-190.

[20] Aggarwal, S., Motevalli, V. (1997). Investigation of an Approach to fuel identification for nonflaming source using light-scattering and ionization smoke detector response. *Fire Safety Journal*, 29 (2-3), 99-112.

[21] Halios, C.H., Helmis, C.G., Assimakopoulos, V.D., Flocas, H.A., Petrakis, M. (2003). Studying indoor air quality in a residential apartment in Athens, Greece. In *8th International Conference on Environmental Science and Technology*, Lemnos Island, Greece, 8-10 September 2003.

[22] Paoletti, L., Berardis, B., Arizza, L., Granato, V. (2006). Influence of tobacco smoke on indoor PM10 particulate matter characteristics. *Atmospheric Environment*, 40 (18), 3269-3280.

[23] Lin, C.C., Peng, C.K. (2010). Characterization of indoor PM10, PM2.5, and ultrafine particles in elementary school classrooms. *Environmental Engineering Science*, 27 (11), 915-922.

[24] Massey, D., Kulshrestha, A., Masih, J., Taneja, A. (2012). Seasonal trends of PM10, PM5.0, PM2.5 & PM1.0 in indoor and outdoor environments of residential homes located in North-Central India. *Building and Environment*, 47, 223-231.

[25] Buonanno, G., Morawska, L., Stabile, L., Viola, A. (2010). Exposure to particle number, surface area and PM concentrations in pizzerias. *Atmospheric Environment*, 44 (32), 3963-3969.

[26] Diapouli, E., Eleftheriadis, K., Karanasiou, A.A., Vratolis, S., Hermansen, O., Colbeck, I., Lazaridis, M. (2011). Indoor and outdoor particle number and mass concentrations in Athens. Sources, sinks and variability of aerosol parameters. *Aerosol and Air Quality Research*, 11 (6), 632-642.

[27] Gao, J., Cao, C., Wang, L., Song, T., Xiang, T., Yang, J., Zhang, X. (2013). Aerosol particles at the oil-heating stage in an experimental kitchen. *Aerosol and Air Quality Research*, 13 (2), 488-496.

[28] Bartušek, K., Dokoupil, Z. (2003). Automatic device for ion fields measurement. *Measurement Science Review*, 3, 75-78.

[29] Jokl, M. (2002). *Healthy Living and Working Environment*. Prague: Academia. [in Czech]

[30] Middleton, R. (1989). *A Negative-Ion Cookbook*. Dept. of Physics, Univ. of Pennsylvania.

[31] Sawant, V.S., Jadhav, D.B. (2012). Laboratory experiments on aerosol removal by negative air ions. In *International Conference on Environmental Science and Technology,* IPCBEE vol. 30. Singapore: IACSIT Press, 63-67.

[32] Fischer, O., Kisova, L., Miadokova, M., Molin, J. (1983). *Physical Chemistry*. Prague: SPN. [in Czech]

[33] Dvorak, J., Koryta, J. (1983). *Electrochemistry*. Prague: Academia. [in Czech].

[34] Sitar, J. (2006). Aerial ions and our health. In *Conference on Humans in Their Earthly and Cosmic Environment*, Upice, Czech Republic, 170-174. [in Czech]

[35] Cernecky, J., Valentova, K. (2012). The effect of ionization on indoor air quality inside of a building. In *Proceedings "Nové trendy v technike ochrany ovzdušia 2012*." Technical University in Zvolen, Slovak Republic, 19-24. [in Slovak]

[36] Obulana, Z., Hostin, S. (2012). Study of oxidizing effect of ozone on vapours of organic substances acetone and ethanol in the air. In *Proceedings "Nové trendy v technike ochrany ovzdušia 2012."* Technical University in Zvolen, Slovak Republic, 86-92. [in Slovak]

[37] Weschler, C.J. (2000). Ozone in indoor environments: Concentration and chemistry. *Indoor Air*, 10 (4), 269-288.

[38] Buonanno, G., Dell'Isola, M., Stabile, L., Viola, A. (2011). Critical aspects of the uncertainty budget in the gravimetric PM measurements. *Measurement*, 44 (1), 139-147.

[39] Mayer, N.K., Lauber, A., Nussbaumer, T., Burtscher, H. (2009). Influence of particle charging on TEOM measurements in the presence of an electrostatic precipitator. *Atmospheric Measurement Techniques*, 2, 81-85.

[40] U.S. Environmental Protection Agency. (2008). *Network Design Criteria for Ambient Air Quality Monitoring*, 366 p. http://www.epa.gov/roe/docs/roe_final/EPAROE_FINAL_2008.PDF.

[41] Brodnianska, Z. (2011). *Gas flow visualization by smoke*. Technical education as a part of general education. Matej Bel University, Banska Bystrica, Slovak Republic, 113-120. [in Slovak].

[42] Piadé, J.J., Wajrock, S., Jaccard, G., Janeke, G. (2013). Formation of mainstream cigarette smoke constituents prioritized by the World Health Organization-yield patterns observed in market surveys, clustering and inverse correlations. *Food and Chemical Toxicology*, 55, 329-347.

[43] Grinshpun, S.A., Mainelis, G., Trunov, M., Adhikari, A., Reponen, T., Willeke, K. (2005). Evaluation of ionic air purifiers for reducing aerosol exposure in confined indoor spaces. *Indoor Air*, 15 (4), 235-245.

[44] Lee, B.U., Yermakov, M., Grinshpun, S.A. (2004). Removal of fine and ultrafine particles from indoor air environments by the unipolar ion emission. *Atmospheric Environment*, 38 (29), 4815-4823.

[45] U.S. Environmental Protection Agency. *National ambient air quality standards (NAAQS).* http://www.epa.gov/air/criteria.html.

[46] World Health Organization. (2000). *Air Quality Guidelines for Europe*, 2nd ed., 273 p. http://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf.

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