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EFFECTIVENESS OF AIR TREATMENT USING A PLATE-TYPE BIOFILTER WITH A CAPILLARY SYSTEM FOR HUMIDIFICATION OF PACKING MATERIAL

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Abstract

In this study a new generation of plate-type laboratory air treatment biofilter is applied for the removal of gaseous contaminants from air. The packing material for the biofilter consists of porous plates arranged vertically one after the other to produce a capillary humidification effect. The porous plate is made of polymer to secure the stiffness of the plate. Birch fibre granules thermally treated in a steam explosion reactor are fixed on both sides of the polymer board. The granules are covered with needle-punched nonwovens. This technology enables to improve the durability of the packing material. During the capillary effect of humidification of the packing material, moisture (bio-medium) is spontaneously rising together with the humidification of the wood fibre and needle-punched nonwovens. Therefore, this system of self-humidification does not consume additional energy, the packing material remains well humidified in case of interruption of technological processes or when power supply is discontinued for any other reasons.

This paper presents findings of the research into the effectiveness of air treatment and microbiological tests involving air contaminated with gaseous acetone, xylene and ammonia contaminants passing through the packing material. The results of the research show high air purification degrees and microbiological activity. The activity of microorganism in the packing material was 1×10^8 CFU/g on average, while air treatment effectiveness was around 91%. It was established that, with the packing material of the aforementioned composition, microorganisms are able to use such combinations as acetone, xylene and ammonia for their metabolism. Bacteria and micromycetes (fungi) were found to be most dominant in the process of destruction of contaminants. *Pseudomonas*, *Arthrobacter*, *Acinetobacter*, *Bacillus* were the genera most frequently identified during the research tests.

Key words: biodegradation, biofilter, capillary, microorganisms, packing material, porosity

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1. Introduction

Emissions of atmospheric contaminants remain to constitute one of the most serious global environmental problems. Contamination with volatile organic and inorganic compounds appears to be particularly pronounced. Only in Europe and the United States of America emissions from industrial and agricultural sectors amount to 703.7 thousand tonnes and 6.96 million tonnes of volatile organic compounds, respectively. Air pollution with gaseous

organic and inorganic compounds deteriorates air quality. In turn, this has negative effects on human health, quality of life and biological diversity. In addition, the contaminants above have a direct influence on climate change (Iordache, Dunea, 2013; Zigmontienė, Zuokaitė, 2010).

Biotechnology is increasingly used for air treatment to reduce acetone, xylene, ammonia and other gaseous emissions. However, the main shortcomings of the currently used biofilters are high aerodynamic resistance of packing materials,

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complicated maintenance of humidity and operating temperature within the packing material, likely obstruction of a mass of microorganisms in the biological packing material, or biomass leaching out of the packing material, big space required for biofilters and large amounts of electricity used to humidify packing materials. There is a lack of complex knowledge of biotechnologies used for air treatment.

The method of biological air treatment employs less expensive, more effective, waste-free and eco-friendly biotechnologies which allow more effective removal of volatile organic compounds from air and neutralisation of unpleasant odours. The issue of the rational use of natural resources and protection of the environment from different contaminants that are harmful not only for the nature but for human beings as well is a main concern of a number of countries of the world (Baltrėnas et al., 2004).

The effectiveness of the biological air treatment process depends on the growth of microorganism cultures in biological media. When contaminants are continuously passing through the biofilter and microorganisms get activated in an initial air cleaning stage, the microorganisms grow in the presence of abundant food (Deshusses, Johnson, 1999; Domsh et al., 2007).

Life can not evolve without carbon, as all chemical compounds existing in a cell are carbon-based compounds. The ability to use organic compounds is seen in representatives of a number of groups of microorganisms rather than in certain forms of narrow specialisation. Hydrocarbon-oxidising microorganisms are an important group of organisms participating in the carbon cycle. Microorganisms are capable of using all organic and inorganic carbon-based compounds for plastic turnover. In this group, bacteria and micromycetes play the key role. Bacteria account for most of them. They feed on different kinds of hydrocarbons and have a short life cycle. The commonly identified genera *Arthrobacter*, *Acinetobacter*, *Pseudomonas*, *Bacillus*, *Flavobacterium*, *Mycobacterium*, *Micrococcus*, *Rhodococcus* represent bacteria capable of oxidising hydrocarbons. There are more than 70 genera of microorganisms capable of degrading hydrocarbons (Chitwood, Deviny, 2001; Figueiredo et al., 2010; Malhautier et al., 2005; Liu et al., 2006).

Quite many hydrocarbon degrading species have been also identified among micromycetes. The most commonly found species of micromycetes are those of the genera *Penicillium*, *Aspergillus*, *Cladosporium*, *Alternaria*, *Botrytis*, *Fusarium*, *Mucor* (Lugauskas, Krasauskas, 2005).

Big quantities of chemicals are used in industries such as chemical, paint and varnishes, oil refining, food, and are emitted to the atmosphere in different ways. Among the most widely spread volatile organic and inorganic compounds are acetone, butanol, toluene, xylene, ammonia, methane,

and others. Human-induced emissions of organic and inorganic compounds result in the formation of photochemical oxidants which, in high concentrations, are harmful to human health, plants and the whole environment (Baltrėnas et al., 2004; Jeong et al., 2008; Paulauskienė et al., 2011).

The effectiveness of biological air treatment largely depends on humidification systems installed in biofilters (Mohseni, Allen, 2000; Shareefdeen et al., 2003). The optimum humidity of a packing material is 60-80%. Packing materials in the currently used biofilters are humidified with the help of humidification sprayers located above the packing material where water is supplied by a pump from a water tank. Such a humidification system is electricity consuming, there develop anaerobic areas inside the filtering layer and there is a risk of biomass leaching out of the packing material. All this reduces the effectiveness of air biofilters. If power supply is interrupted or a technological process is stopped, humidification is discontinued and the packing material can become too dry and crack (Zagorskis et al., 2012).

The purpose of the research is to measure the effectiveness of biofiltration of air contaminated with gaseous acetone, xylene and ammonia contaminants, using a capillary humidification system for a packing material consisting of porous plates, to identify microorganisms participating in the process of destruction of contaminants and to measure their quantity.

2. Materials and methods

A laboratory biofilter bench used for research tests presents a completely new structure which enables reduction of aerodynamic resistance, whereas a capillary packing material humidification system enhances moisture retention properties of the packing material and reduces energy costs.

The operating principle of the laboratory biofilter (Fig. 1) is based on the decomposing properties of the microorganisms which break down gaseous contaminants in the biofilter's packing material down to CO₂ and H₂O. Contaminated air is supplied to the biofilter through a 100 mm diameter air duct for contaminated air supply (1). Contaminated air is blown to the biofilter by a ventilator (3) installed in the contaminated air duct. There is a valve (2) fitted in the air duct which regulates the rate of airflow supplied and, at the same time, the yield of air. The contaminated airflow then proceeds to a biofilter's cassette (16) which is loaded with a packing material consisting of porous plates. A perforated plate (15) evenly distributes the airflow over the entire volume of the packing material. The contaminated air flows through the porous plates submersed in a liquid medium and arranged next to each other with 4 mm distance between them. Having passed the biofilter's cassette (16) charged with the packing material, the cleaned airflow then enters a 100-mm diameter clean air discharge pipe (13) and

exits to the atmosphere. The cassette is fixed within the device with fastenings (7). The pipes for contaminated and cleaned air have sampling holes (6) where the rate and temperature of the airflow, as well as concentration levels of contaminants supplied to and discharged from the biofilter, are measured. Excessive biomass is removed from the biofilter through a biomass discharge valve (10). The required temperature of supplied airflows is maintained by a channel air heater (18) equipped with a heat regulator and sensor (4, 5). The biomedium temperature is maintained with the help of a biomedium heating element (14). A solution saturated with biogenic elements is supplied to the biofilter from a tank (9) equipped with adjustable valves (10, 12) and a supply hose (11).

The main component of the biofilter is a cassette which is loaded with a packing material consisting of porous plates. Cassette dimensions are 900×200×200 mm. The packing material consists of porous plates arranged vertically next to each other to produce a capillary humidification effect. The plates have 4 mm gaps between them. The arrangement and composition of the plates are shown in Fig. 2.

Thermally processed birch fibre granules are fixed on both sides of the solid polymer board. The thermal processing of birch fibre is necessary to maintain its durability.

The birch fibre is obtained through thermal processing of birch sawdust in a steam explosion reactor (at 32 bar pressure and 235°C temperature). Thus, the chemical structure of the wood is changed preventing the birch fibre from rot in a humid environment. This extends the durability of the packing material of the biofilter. In order to increase plate capillarity and biomedium lift, the birch fibre is covered with a needle-punched nonwoven fabric. The dimensions of the porous plate in the biofilter are 900×200×10 mm. The detailed composition and thickness of the porous plate is shown in Fig. 2b. The physical properties of the materials used for biological air treatment are described in Table 1.

The relative and absolute humidity of the materials was determined using the weight (mass) loss method. The porosity was measured using the saturation method and the density was determined by weighing. The materials were selected basing on their inner structures. The structure of the material was determined by electron microscopy. The electron microscopy was carried out using the field emission scanning electron microscope JEOL ISM – 7600 F (magnification: 25 to 1000000, electron accelerating voltage: 0.1 to 30kV, image acquisition: 5120×3840 pixels). The structure of the tested materials is shown in Fig. 3.

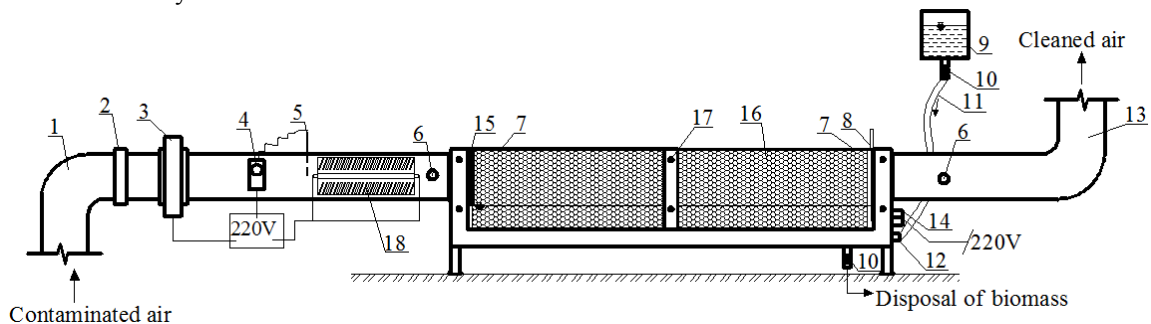


Fig. 1. Diagram of a plate-type air treatment biofilter with a capillary system for humidification of packing material

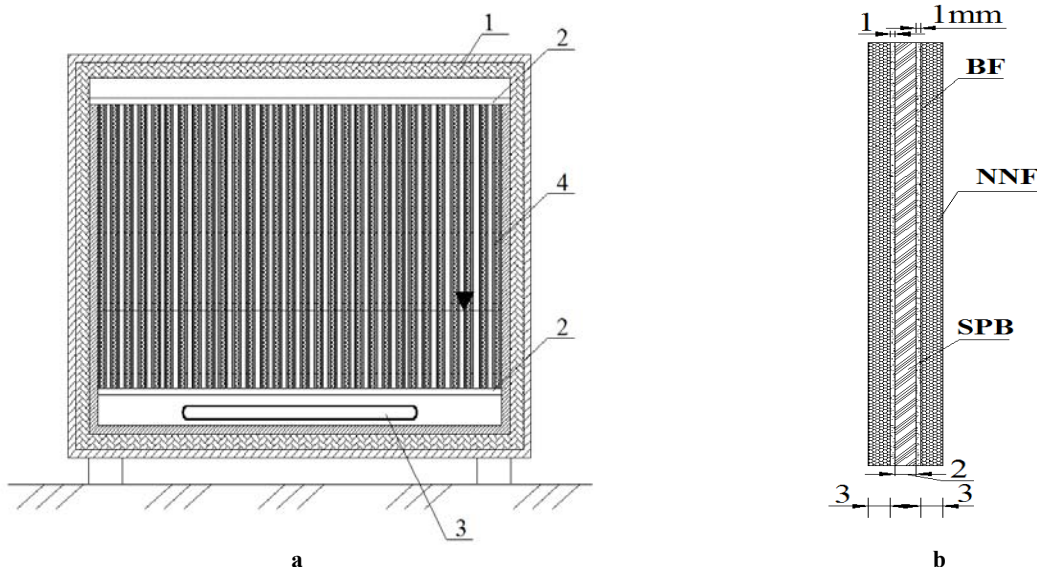


Fig. 2. Plate arrangement and composition diagram: a – plate arrangement (1 – cassette body, 2 – plate fastening, 3 – biomedium heating element, 4 – porous plate); b – porous plate composition (SPB – solid polymer board, BF – birch fibre, NNF – needle-punched nonwoven fabric)

Table 1. Physical properties of materials used for biological air treatment

Material	Relative humidity, %	Absolute humidity, %	Porosity, %	Density, g/cm ³
Needle-punched nonwovens	3.1	8.4	89.2	0.13
Birch fibre	10.6	13.3	72.0	0.14

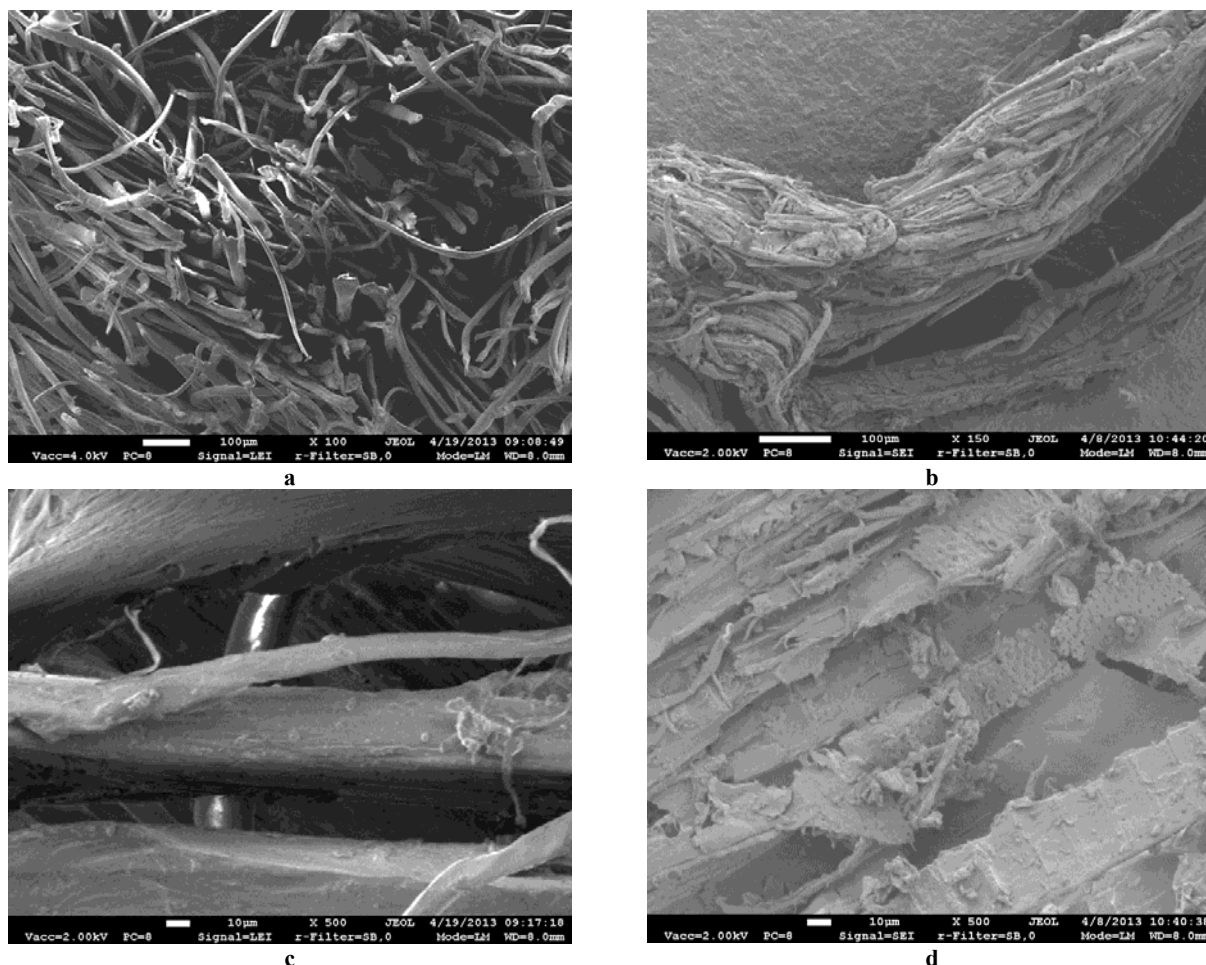


Fig. 3. Structure of the research material: a – needle-punched nonwoven fabric (magnified 100 times), b – birch fibre (magnified 150 times), c – needle-punched nonwoven fabric (magnified 500 times), d – birch fibre (magnified 500 times)

2.1. Maintenance of humidity in the plate-type biofilter

The porous plates of the biofilter's cassette were submerged in a solution saturated with biogenic elements (Fig. 2a). The solution used for research tests was composed of K_2HPO_4 (1g), KCl (0.5g), $MgSO_4 \cdot 7H_2O$ (0.5g), $FeSO_4 \cdot 7H_2O$ (0.1g), $NaNO_3$ (0.90g), distilled water (1000g) (Baltrėnas and Zagorskis, 2009). The porous plates were submerged to a depth of 50 mm, whereas the total height of the plate was 200 mm. The porous structure of the plates and the existing gaps (4 mm) between them produced a capillary humidification effect.

During the capillary effect humidification of the packing material, the solution (biomedium) was spontaneously rising and humidifying the wood fibre and needle-punched nonwoven fabric. Therefore, this system of self-humidification does not consume additional energy, the packing material remains well humidified in case of interruption of technological

processes, repairs, or when power supply is discontinued for any other reasons.

The humidity content of the packing material was determined using the electrical resistance method. Method error margin was $\pm 0.1\%$. The relative air humidity was determined using the humidity meter M0290. The meter measures humidity 0 to 99.9% with $\pm 0.1\%$ accuracy. Humidity was measured every day at different points of the porous plates. The humidity of the packing material was 60–70% at different points.

2.2. Determination of biomedium pH

The proper pH level of the biogenic solution (biomedium) was maintained using buffer solutions (Baltrėnas, Zagorskis, 2010). During the research tests, solution pH was 7 ± 0.01 . The pH level was determined in accordance with Standard LST ISO 10523, using Mettler Toledo pH meter. The meter measures pH 0 to 14 with ± 0.01 pH accuracy. The pH levels were measured every day.

2.3. Determination of biomedium temperature

In order to maintain the biomedium at a constant temperature of 30 °C, the biofilter has a heating element in the bottom part. To prevent the biomedium on the packing material from being cooled down by the air supplied to the biofilter, the contaminant supply pipe has a heater which ensures airflow supply to the biofilter at a steady constant temperature of 30 °C. The layout of the heating elements is shown in Figs. 1 and 2a.

2.4. Activation and determination of the effectiveness of packing material

During the research tests, contaminated airflow was passing the biofilter's packing material at a rate of 0.08 m/s. At the given rate, the effectiveness of the device was 12 m³/h. The airflow rate was calculated using Testo 400 measuring unit (Germany) with a thermocouple. Thermocouple measurement accuracy is ±0,01m/s for 0 to 2 m/s airflow rate. In order to increase the number of microorganisms, the packing material was activated for 18 days. On the first day of activation, air contaminated with acetone vapour was supplied to the biofilter 4 times for 15 minutes each time. The contaminant vapour concentration of the supplied air was around 15.9 mg/m³. Later on, the rate of contaminant dilution was reduced every day to increase concentration of the organic compound by 20±5 mg/m³ and the duration of acetone supply was extended up to 1 hour. At the end of the experiment, on day 24, the initial concentration of the contaminant was increased up to 430 mg/m³. Samples were taken before and after biofiltration at the sampling holes. Then the contaminant was replaced by xylene and the experiment was continued with gradual increase of xylene vapour concentration in the air supplied to the biofilter. The experiment with the supply of air contaminated with xylene vapour lasted for 10 days, during which the initial concentration of the contaminant vapour was increased from 55±5 to 340±34 mg/m³. The experiment with xylene was followed by supplying the air contaminated with ammonia vapour. The experiment with ammonia lasted for 10 days, during which the initial concentration of the contaminant vapour was increased from 105±10 to 315±31 mg/m³.

Different concentrations of contaminants were achieved by diluting with water and heating on an electric hot-plate. The generated contaminant vapour was supplied to the biofilter through the air duct for contaminated air.

The captured air samples were pumped out through a stainless steel tube ($d = 5$ mm, $l = 30$ cm) at a speed of 0.25 l/min to MiniRae 2000 photoionisation detector with a 11.7 eV gas discharge lamp. After completion of the pumping, the concentration of the contaminant was displayed on the monitor of the detector.

The concentration of the contaminants was determined using the method of photoionisation. The concentration of acetone vapours was measured using MiniRae 2000 of RaeSystems (United States of America). The detector measures concentrations from 0 to 7000 mg/m³ with 0.1 mg/m³ accuracy for concentration ranging from 0 to 100 mg/m³ or 1 mg/m³ accuracy for concentrations exceeding 100 mg/m³ – 1000 mg/m³.

Once the concentrations of the organic substances at issue were determined in the above-described manner, effectiveness (E), filtration time (FL), efficiency (N) of the biofilter were calculated as follow (Eqs. 1-3):

$$E = \frac{C_0 - C}{C} \cdot 100 \% \quad (1)$$

where: C_0 – pre-charge concentration, mg/m³;
 C – post-charge concentration, mg/m³;
 E – effectiveness, %.

$$FL = \frac{V}{Q} \quad (2)$$

where: FL – filtration time, s;
 Q – gas flowrate, m³/h;
 V – packing material (charge) volume, m³.

$$N = \frac{Q(C_0 - C)}{V} \quad (3)$$

where: N – efficiency, gm³ h⁻¹.

2.5 Microbiological tests

Microbiological tests were conducted in parallel with the tests for determination of biofilter's effectiveness. The purpose of the microbiological tests was to identify the number of cultures of microorganisms. Samples were taken from the lower, middle and upper parts of the biofilter's plates every 2–3 days. A total of 54 samples of biofilter packing material were taken (3 samples 18 times). In case of acetone filtration, microbiological tests took 29 days, in case of xylene and ammonia – 10 days in each case.

In order to identify microorganisms and calculate their quantities, the wash-off method (suspension dilution) was used (as described in the available manuals). A 1g piece was taken from each sample, put into a flask containing 90 ml of 0.8% NaCl, and prepared for dilutions. In order to compare different samples, the tested material was dried to a constant weight and then the number of microorganisms per gram dry material of the biofilter was calculated. In addition, the area of the weighed sample was measured and the number of microorganisms per square centimetre was calculated.

Micromycetes were identified in the agarised malt wort medium. Then the Petri dishes containing the agar medium were incubated at a temperature of +28°C for 5-7 days.

Pure micromycete cultures were identified using classical methods according to the following literature: references for micromycetes (Chaverri and Samuels, 2003; Domsch et al., 2007; Ellis, 1971; Pečiulytė and Bridžiuvienė, 2008; Pitt, 1979; Samson and Frisvad, 2004; Watanabe, 2002). Yeasts were isolated in Sabouraud agar with Chloramphenicol (Liofilchem, Italy) and Rose Bengal CAF agar (Liofilchem, Italy) nutrient media. Then the seeds were incubated on Petri plates at a temperature of +28°C for 3-4 days. Yeasts were identified using the Api 20 C AUX (bioMérieux, France) identification systems.

In order to isolate bacteria from the analysed samples, nutrient agar (NA), Cetrimide agar (*Pseudomonas* selective agar) and *Bacillus cereus* agarised media were prepared. Bacterial culture suspensions were diluted at 1:10, 1:100, 1:1000, 1:10.000, 1:100.000, 1:1.000.000, 1:10.000.000, 1:100.000.000, 1:1.000.000.000, 1:10.000.000.000. Then 0.1 ml of the suspension was tipped onto the agar surface and brushed in on Petri plates. The seeds were incubated at a temperature of +28°C for 2-4 days. The isolated bacteria were identified according to their morphological, biochemical and physiological properties, and then compared with data in literature. Bergey's Manual of Systematic Bacteriology was used as a descriptor for bacteria (Palleroni, 1984; Garrity, 2005).

3. Results and discussion

The main component of the biofilter is its packing material. The biodegradation of organic and inorganic compounds requires humidification of the packing material. Therefore, one of the key requirements for packing materials is a large specific surface area. Billions of microorganisms contained in a biofilm, which develops on the surface of the packing material after a certain time, decompose organic compounds to hydrocarbon and water (Chan, 2006). Therefore, the larger is the specific surface area, the bigger is the number of microorganisms in the packing material.

The structure of the research material was determined by electron microscopy. The porous structure of the packing material enables a capillary effect when a solution saturated with biogenic elements rises up via capillaries thus humidifying the packing material and performing the function of a biomedium carrier. This is due the fact that molecules of liquids have stronger forces to attract surface molecules as compared to molecules in vapours. As a result, the liquid is rising up due to surface tension forces.

The analysis of the structure of materials has revealed that most of needle-punched nonwovens consisted of thin fibres of 15 to 25 µm in thickness.

Gaps between the fibres exceeded the thickness of the fibres by 5 to 10 times (Fig. 3a). Such an arrangement of the fibres allows for the formation of a biofilm without anaerobic zones that are harmful for microorganisms. The chaotic pattern of fibres enables to increase the specific surface area of the material and, at the same time, the volume of biomedium in the material. In the structure of the material magnified by 500 times we can see fibres of 120–180 µm in thickness forming 10–30 µm capillaries (Fig. 3c). Similarly, thermally processes birth fibre also has irregular surface, porous structure and, at the same time, larger specific surface area (Fig. 3b). The structure of wood fibre capillaries is not even. Their size varies from 10 to 50 µm (Fig. 3c). The surface structure of the fibre enables biomedium to flatten against the material and form a biofilm. In turn, microorganisms in the biomedium are capable of taking organic carbon from birch fibre.

In order to reduce biofiltration costs, packing material propagates natural microorganisms. Therefore, in order to achieve high effectiveness of the removal of gaseous contaminants from air, it is necessary to activate the packing material. For the purpose of microbiological tests, 3 control samples of the packing material were taken. The average number of microorganisms determined in the samples was $(3.7 \pm 0.4) \times 10^3$ CFU/g. The tests showed 30% effectiveness of removing acetone vapours from the air with inactivated packing material consisting of birch fibre and needle-punched nonwovens in the biofilter. This air cleaning effectiveness was due to absorption and adsorption processes taking place in the biofilter. Accordingly, the biological packing material of the biofilter was activated by supplying the air contaminated with organic contaminants to the packing material (Baltrėnas et al., 2004). The biological packing material was considered to be bioactivated once covered with a thin layer (5–30 µm) of a biofilm formed by microorganisms.

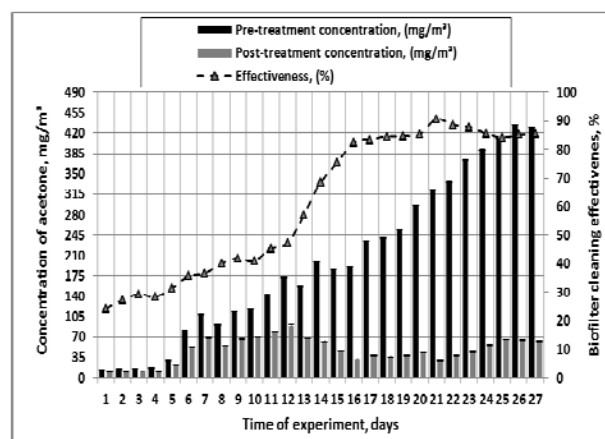


Fig. 4. Contaminant concentrations and biofilter cleaning effectiveness against time when biofilter is supplied with airflows contaminated with acetone vapour

According to data in Fig. 4, high air cleaning efficiency can be achieved as soon as 13 days after

activation of the packing material. The packing material was activated with acetone-contaminated air. At the beginning of the activation, the initial concentration of the contaminant was 15.9 mg/m^3 . It was increased to reach 430 mg/m^3 at the end of the experiment. As we can see from data in Fig. 4, the cleaning effectiveness of the biofilter gradually increased until day 13. Until day 5, the growth of microorganisms was seen to be in the lag phase which depends on how microorganism cultures get activated in biomed. During this phase, microorganisms adapted to the new conditions. Starting with day 6 to day 13, the growth of microorganisms was in the log (exponential) phase demonstrating the increasing air cleaning effectiveness (Zigmontienė, Žarnauskas, 2011). The tests revealed that from the 13th day onwards the number of microorganisms reached the level when air cleaning efficiency stood high at 85.3%. A further increase in the initial concentration of acetone from 185 to 430 mg/m^3 only slightly improved the biofilter's efficiency up to 90%.

Biofilter's bacteria, yeasts and micromycetes play the key role in degradation of organic compounds emitted to the environment due to natural or industrial processes. The biodegradation of organic substances results in the formation of new organisms (catabolism) and oxidation of the components to carbon dioxide and water (Baltrėnas et al., 2004). All life processes of living things take place in water, i.e., in a thin water film developing on the surface of a packing material (Malhautier et al., 2005).

Supply of organic substances to the biofilter increases activity of the packing material. However, this activity decreases with reduced concentrations of the supplied contaminant and the layer of biomass on the packing material becomes thinner. The synthesis of organic compounds in the biofilm requires the transfer of the substrate (contaminant) from the gas phase to liquid.

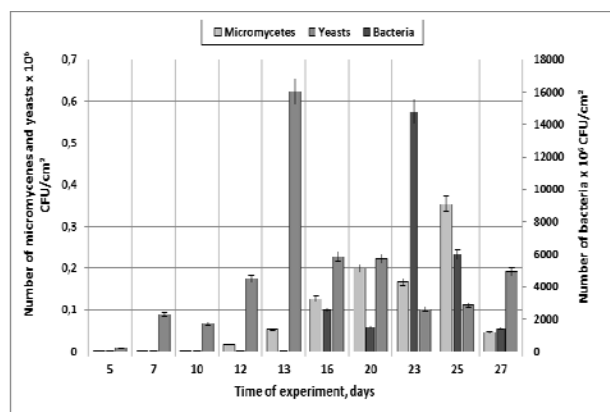


Fig 5. Number of microorganisms against time of supplying airflows contaminated with acetone vapour to the packing material

From day 13 to day 17 of the experiment, the effectiveness of removing acetone vapour from the

air changed from 82.5% to 85.3%. The highest effectiveness of 90.7% was recorded on day 18 of the experiment. This was determined by increasing the number of bacteria up to $1.48 \cdot 10^{10} \text{ CFU/cm}^2$, as shown in Fig. 5. When concentrations were further increased from 320 mg/m^3 to 429 mg/m^3 , the effectiveness of biofiltration started dropping down and was 85.5% at the end of the experiment. This decrease in effectiveness was determined by a decreasing number of micromycetes and bacteria. At the end of the experiment, the number of micromycetes was $4.5 \cdot 10^4 \text{ CFU/cm}^2$, and the number of bacteria was $1.44 \cdot 10^9 \text{ CFU/cm}^2$. Micromycetes of *Penicillium sp.*, *Aspergillus niger*, *Aureobasidium sp.*, *Geotrichum sp.* were found to be the dominant species on the surface of porous plates.

Data from experiment involving supply of air contaminated with xylene through the packing material composed of birch fibre and needle-punched nonwovens is presented in Fig. 6. It was found out that the effectiveness of removing xylene from the air after 10 days of the experiment was similar to that of acetone removal and reached 87.5%. This could be due to a similar coefficient of gas solubility in water. The dependence of gas solubility in biomed. on pressure is defined by Henry Law, who states that the solubility of a gas in a liquid is directly proportional to the pressure of that gas. Increased temperature causes a decrease in the solubility of gases in media, and vice versa (Miller and Allen, 2004).

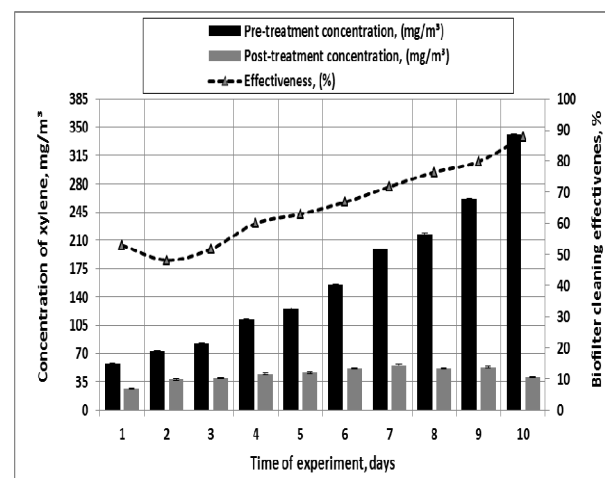


Fig 6. Contaminant concentrations and biofilter cleaning effectiveness against time when biofilter is supplied with airflows contaminated with xylene vapour

Fig. 6 demonstrates that the effectiveness of biofiltration was gradually improving until the end of the experiment. The initial concentration of the contaminant was 57 mg/m^3 . It was gradual increased to reach 340 mg/m^3 at the end of the experiment. At 73 mg/m^3 concentration of xylene vapour in the air, the number of micromycetes was $5.6 \cdot 10^4 \text{ CFU/cm}^2$, yeasts – $2.91 \cdot 10^4 \text{ CFU/cm}^2$, and bacteria $6.8 \cdot 10^6 \text{ CFU/cm}^2$.

In the course of the experiment, significant fluctuations in the number of micromycetes on the

packing material of the biofilter were identified. At the beginning of the experiment, the number of micromycetes did not decrease. Rather, it appeared to have slightly increased. However, a decrease in the number of micromycetes was detected on day 7 of the experiment, notably in the upper and lower parts of the porous plate. Predominance of bacteria was detected from day 10 onwards; when the number of bacteria reached the maximum values while the number of micromycetes went down to usual value (Fig. 7).

Bacteria and micromycetes play the key role in the removal of contaminant from the air. Therefore, the bigger is the number of bacteria and micromycetes in the biological packing material, the higher is the effectiveness of biofiltration. The number of bacteria depends on the concentration of the contaminant supplied. The concentration of the contaminant was gradually increased from 15 to 30 mg/m³ every day.

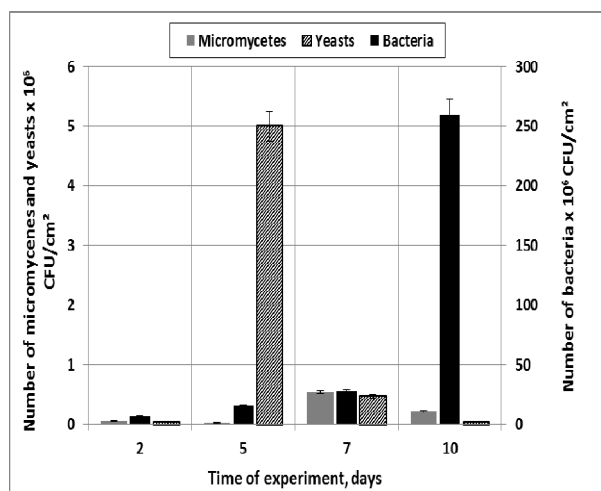


Fig. 7. Number of microorganisms against time of supplying airflows contaminated with xylene vapour to the packing material

An increase in effectiveness was gradual as well. This can be explained the growing number of bacteria in the packing material which has doubled (Fig. 7). At the end of the experiment, the effectiveness of air cleaning in the biofilter reached 87.9% as a result of an increase a bacteria up to $2.6 \cdot 10^8$ CFU/cm². Types of the micromycetes detected were similar to those found in case of acetone removal from the air. Fungi of the genera *Paecilomyces variotii* and yeasts of the genera *Aureobasidium* and *Geotrichum* kept dominating.

It can be presumed that activity of microorganisms is reduced, by lower contaminant's coefficient of transfer from the gas phase to liquid. Such a situation may occur in case of failure/delayed adaptation of microorganisms to new conditions, i.e., in case of change of the contaminant supplied.

Fig. 8 illustrates concentrations of ammonia in the air supplied to and discharged from the device, as well as air cleaning effectiveness against time when the rate of airflow in the packing material is 0.08 m/s.

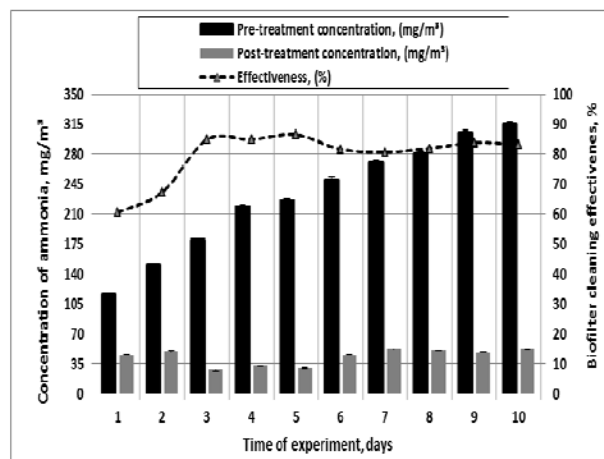


Fig. 8. Contaminant concentrations and biofilter cleaning effectiveness against time when biofilter is supplied with airflows contaminated with ammonia vapour

During the experiment, the cleaned air yield was 1.1 l/s. Biological packing material and contaminated air contact time was 11.25 s. The effectiveness of the biofilter was significantly improving during the first three days of the experiment from 60.5% to 84.9%.

Humidity of the packing material in the biofilter was kept at 60–70% during the whole duration of the experiment. This caused a great number of microorganisms in the packing material.

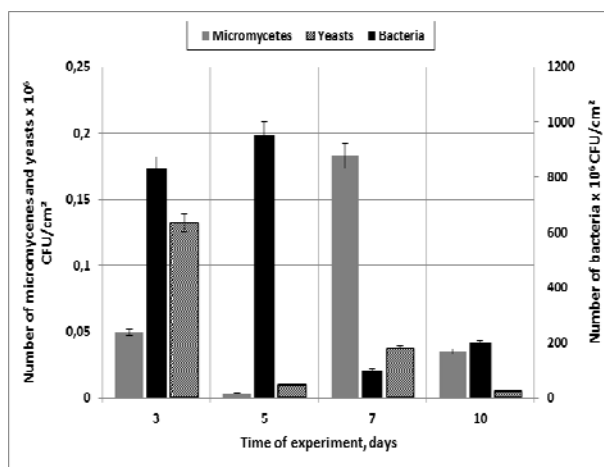


Fig. 9. Number of microorganisms against time of supplying airflows contaminated with ammonia vapour to the packing material

On day 4 and 5, cleaning effectiveness remained stable at 85.8% on average. This was determined by an increase in the number of bacteria up to $9.5 \cdot 10^8$ CFU/cm². Later on, the number of bacteria dropped down to $9.9 \cdot 10^7$ CFU/cm² (Fig. 9) and was followed by a decrease in the cleaning effectiveness down to 80.7%. On day 10 the number of bacteria reached $2.0 \cdot 10^8$ CFU/cm², and the cleaning effectiveness improved to reach 83.3%. On all days of the experiment, concentrations of ammonia in the discharged air were below 100 mg/m³, ranging from 30.3 to 52.6 mg/m³.

Certain changes were also identified in the types of micromycetes. In addition to the above-mentioned dominant species there again appeared *Penicillium sp.* and white colonies-forming fungus *Myrothecium sp.* which was not yet fully identified. Yet, fungi *Geotrichum sp.* and *Paecilomyces variotii* remained to be dominant.

Therefore, on the basis of the above-described experiments, it can be assumed that the humidification system at issue ensures avoidance of insufficient humidification, over-drying or cracking of the packing material which facilitates air flowing capacity and increases the activity of microorganisms. As the capillary humidification of the packing material does not require any electrical elements such as water pumps or time relays, the biofilter is safer and simpler to operate.

4. Conclusions

1. The research has revealed that the use of capillary packing material consisting of porous polymer plates, wood fibre and nonwovens enables to achieve high air cleaning effectiveness of up to 93%. This humidification system does not require mechanical humidifying of the packing material which reduces energy costs.

2. In the process of acetone, xylene and ammonia degradation, the predominance of bacteria and micromycetes capable of effective destroying of volatile organic and inorganic compounds have been identified. The average number of such bacteria and micromycetes was $8.5 \cdot 10^9$ and $2.0 \cdot 10^8$ CFU/cm², respectively.

3. The research has demonstrated that the packing material composed of porous plates, wood fibre and nonwovens can be used for biological removal of gaseous contaminants from the air. The high activity of microorganisms in the packing material is ensured by the sorptive and physical properties of the packing material.

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