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EFFECTIVENESS RESEARCH ON A WAVY LAMELLAR PLATE-TYPE BIOFILTER WITH A CAPILLARY SYSTEM FOR THE HUMIDIFICATION OF THE PACKING MATERIAL APPLYING INTROINDUCED MICROORGANISMS

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Abstract. To conduct research, a new generation plate-type air treatment biofilter for removing gaseous pollutants from air has been applied under laboratory conditions. A distinguishing feature of the packing material of the biofilter includes wavy lamellar polymer plates placed to each other and producing a capillary effect of humidification. While having such an arrangement, wavy lamellar plates also have rather wide spacing (6 mm), and therefore the employment of the structure of the plate-type packing material decreases the aerodynamic resistance of the device. A wavy porous plate is made of a polymer plate that ensures stiffness. Both sides of the wavy lamellar polymer plate have attached *steam exploded* birch fiber pellets under which, to increase plate capillarity, not-woven caulking material is put. This technological decision allows effectively enhancing the durability of the biopacking material. The work presents the results of research on the efficiency of the biodestruction process of acetone, xylene and ammonia. With reference to the conducted investigation, the high efficiency of air treatment and microbiological activity has been established. When pollutant gases (acetone, xylene and ammonia), under a velocity of 0.08 m s^{-1}, passed through the biopacking material, microbiological activity in the material reached on average 1×10^8 cfu/cm^2, and air treatment efficiency made 90.7%.

Keywords: biofilter, air treatment efficiency, capillary, biopacking material, microorganisms.

Introduction

The branches of industry like chemistry, varnishes and paints, food and oil refining terminals use a large amount of chemical materials that find different ways to be released into the atmosphere. Acetone, butanol, toluene, xylene, ammonia methane, etc. are among the most common volatile organic and inorganic compounds emitted to the atmosphere due to human factors and forming photochemical antioxidants, a high concentration of which is harmful to human health, plants and the environment in general (Baltrėnas *et al.* 2004; Jeong *et al.* 2006; Paulauskienė *et al.* 2011).

The emission levels of volatile organic compounds (acetone, xylene) to the atmosphere are significantly lower than those of combustion products, for example, CO_2, CO, SO_2 and NO_2. However, the impact of VOC on humans and the natural environment is much stronger (Pielech-Przybylska *et al.* 2006; Paulauskienė *et al.* 2011; Yang *et al.* 2010). Also, the increasing amounts of VOC directly influence fluctuations in climate and are related to the depletion of the ozone layer (Delhomenie, Heitz 2005). Thus, the decontamination of these pollutants is an important task leading a reduction in a negative impact on the environment.

VOC (acetone, xylene) and ammonia are most frequently emitted from wastewater treatment plants in a number of industries such as foundries, chemical industry, electronics, paints, etc. (Wu *et al.* 2006; Jun, Wenfeng 2009).

At the moment, biological air treatment using certain cultures of microorganisms is one of the most promising air cleaning methods (Baltrėnas, Zagorskis 2009).

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Biofilters are employed for removing butanol, acetone, xylene, toluene and other volatile organic compounds from air. Equipment may be efficient when the concentration of the pollutant does not exceed 500 mg/m^3 (Baltrėnas, Zagorskis 2010).

The effectiveness of the biological air treatment process depends on the growth of microorganism cultures in the medium. At the initial moment of air treatment, under a continuous supply of pollutants to the biofilter and while activating microorganisms, they encounter surplus food and therefore grow (Domsh *et al.* 2007).

To initiate the biodestruction of pollutants in the biofilter and to stimulate the development of microorganisms, appropriate conditions are required. Physical factors such as humidity and temperature often affect the growth and reproduction of microorganisms (Baltrėnas *et al.* 2004). Water, in this case, is the most powerful medium where the metabolism reactions of materials take place; moreover, all chemical reactions occurring in live microorganisms necessitate water that makes approximately 75% and even more of the whole biomass (Zigmontienė, Žarnauskas 2011).

The fundamental element of the biological air treatment device is a filtering medium necessary as substrate for microorganisms, and at the same time, providing them with the needed nutrients. In practice, as the filtering media, the packing materials of natural origin, including compost, peat, wood chips, bark and activated sludge, are applied (Zigmontienė, Baltrėnas 2004).

The humidification systems arranged in biofilters have a strong impact on the efficiency of biological air treatment (Mohseni, Allen 2000; Shareefdeen *et al.* 2003). The optimal humidity of the packing material is 60–80%. At present, the applied biofilters use the humidified packing material employing the above placed humidification nozzles, water to which is supplied to the pump from a water tank. While applying the introduced humidification system, a large amount of electricity is used, anaerobic areas occur inside the filtering layer and a possibility of leaching biomass from the packing material arises, which causes a decrease in the efficiency of biofilters used for air treatment. In the events of electricity failure or the crash of the technological process, the packing material is not humidified and therefore may parch or cracks may appear.

The humidity of the packing material depends on the type of the material and the humidification system installed into the biofilter. In our researched case, the biofilter contains the implemented capillary system for the humidification of the packing material, i.e. the medium in the biofilter, due to narrow spacing (6 mm) between wavy lamellar plates, has risen with the help of not-woven caulking material and birch fiber pores.

One of the main requirements for biological air treatment equipment are the low aerodynamic resistance of the packing material. Aerodynamic resistance depends on a variety of factors like the porosity, form, fraction and humidity of the packing material. The aerodynamic resistance of the packing material also affects the treatment efficiency of the biofilter (Eldon *et al.* 2010). Lower aerodynamic resistance determines a better distribution of oxygen, which is involved in the metabolic processes of nutrients, in the packing material. Regular search for the methods that improve the aerodynamic processes occurring in the packing material without reducing the effectiveness of treatment is taking place (Baltrėnas, Zagorskis 2009).

Time for contact between the biopacking material and pollutant seems to be an important aspect of optimal and efficient air treatment. The lower is the air flow rate in the biofilter, the longer takes time for contact between the polluted air and the used packing material, which therefore increases the effectiveness of the biodestructive process.

Temperature is a crucial factor having an influence on the proliferation of microorganisms and on the intensiveness of biochemical reactions. Different groups of microorganisms have adapted for living under different temperatures. The microorganisms involved in the processes of pollutant biodestruction fall into a few categories, including psychrophilic, mesophilic and thermophilic. Research was conducted under a temperature of 25–30 °C in the medium and air in the biofilter. The maintained temperature was favourable for the growth and development of mesophilic microorganisms (Boswell 2010).

The conducted investigation has been aimed at using a capillary system for the humidification of the packing material made of porous wavy lamellar plates so that to establish the efficiency of the biofilter while emitting the air polluted with acetone, xylene and ammonia emissions and propagating introinduced microorganisms.

1. Research methods

1.1. Structure of the Biofilter

To conduct research, a bench of a laboratory biofilter has been employed (Fig. 1). The biofilter stands out for completely new design that allows reducing the aerodynamic resistance of the device, and the capillary system for humidifying the packing material improves the qualities of humidity retention in the packing material as well as decreases energy expenses.

The packing material of the biofilter uses wavy lamellar plates which, while moving in the contaminated air flow, increase contact between the employed pollutants and wavy lamellar partition walls containing microorganisms.

The structure of the biofilter consists of the biopacking material (cassette has been made of wavy lamellar

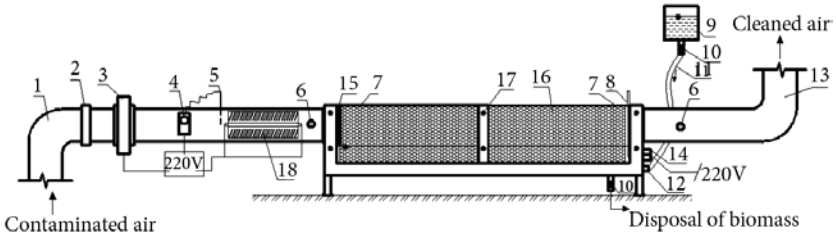

Fig. 1. Scheme for a wavy lamellar plate-type air treatment biofilter with a capillary system for the humidification of the packing material

plates), the system for maintaining the humidity and temperature of the packing material in the filter (air heater with a control thermostat and sensor; heating element of the bio-medium), ventilator (maintains a constant air flow rate in the packing material of the biofilter), air ducts for supplying and removing air from the device, air flow control valve (the adjustable air flow rate and, simultaneously, the supplied air rate), perforated card (evenly distributes air flow over the total volume of the packing material) and drain valve (excess biomass is removed from the biofilter).

The operation principle of the lab biofilter (Fig. 1) refers to the packing material in which microorganisms decompose gaseous emissions to CO_2 and H_2O. The polluted air is supplied to the biofilter through the air duct 100 mm in diameter (1). Air flow moves through the biofilter because of the ventilator arranged in the air duct for supplying the polluted air (3). The valve (2) is placed in the air duct of the polluted air and adjusts air flow and supplied air rates. Next, the polluted air flow reaches the cassette of the biofilter (16) charged with the packing material made of porous plates. The perforated plate (15) is used for evenly distributing air flow throughout the total volume of the packing material. The polluted air moves between porous plates immersed in a liquid medium and placed in 4mm apart. The purified air stream passes through the cassette of the biofilter (16) charged with the packing material, reaches the purified air duct 100 mm in diameter and is removed to the environment. The cassette is attached to the device with the help of fasteners (7). The ducts of the polluted and purified air have installed sample slots (6). These places have the established air flow rate and temperature as well as the concentrations of pollutants supplied to and removed from the biofilter. The excess biomass is removed from the biofilter through the drain valve of the biomass (10). The required temperature of the supplied air flow is supported by an air duct heater (18) equipped with a control thermostat and sensor (4, 5). The temperature of the bio-medium is maintained using the heating element (14). To supply a nutrient-rich solution to the biofilter, a tank with adjustable valves (10, 12) and a hose (11) have been installed.

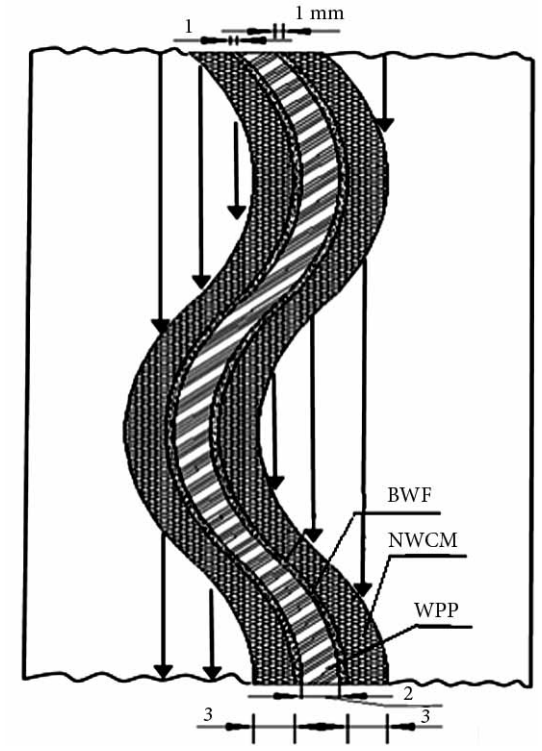

Fig. 2. The structure of the porous plate (WPP – wavy lamellar polymer plate, BWF – birch wood fiber, NWCM – not-woven caulking material); air flow direction

The main element of the biofilter is a cassette made of wavy lamellar plates onto which the biopacking material, i.e. not-woven caulking material and wood fiber, is attached. The dimensions of the cartridge make 900×200×200 mm.

The packing material consists of wavy porous plates vertically arranged next to each other and making a capillary humidifying effect of the packing material. Such an arrangement of the plates points to 6 mm spacing. The structure of the plates is shown in (Fig. 2).

Both sides of the wavy lamellar polymer plate have attached steam exploded birch fiber pellets. The steam explosion of birch fiber is necessary for maintaining its durability. Birch fiber is received through the steam explosion of birch sawdust in the reactor under the pressure of 32 bars and a temperature of 235 °C. Thus, changes in the chemical structure of wood prevent birch fiber from decay in a humid environment, and therefore the durability of the packing material of the biofilter increases. To enlarge the capillarity of the plate along with the uplift height of

the bio-medium, not-woven caulking material is attached to birch fiber. The dimensions of the porous plate in the bio-filter make 900×200×10 mm.

The relative and absolute humidity of materials has been established with reference to the weight based on a decrease in the amount of mass. Porosity has been found out with the help of saturation, whereas density – employing the weighing method.

Choosing materials has been determined by their inner structure. The composition of the material has been defined applying the method of electron microscopy. Scanning electron microscopy has been done using field emission scanning electron microscope JEOL ISM – 7600 F magnifying from 25 to 1 000 000 times. The accelerating voltage of electrons varied from 0,1kV to 30 kV. Image resolution was up to 5120×3840 pixels. The structure of the investigated materials is shown in (Fig. 3) and (Fig. 4).

1.2. Maintaining humidity in the biofilter with a wavy lamellar structure

The biofilter is immersed in a solution saturated with biogenic elements (Fig. 1). The solution used for research purposes has been made of K_2HPO_4 – 1 g, KCl – 0.5 g, $MgSO_4 \times 7H_2O$ – 0.5 g, $FeSO_4 \times 7H_2O$ – 0,1 g, $NaNO_3$ – 0.90 g and 1000 g distilled water (Baltrėnas, Zagorskis 2009; Trejo-Aguilar *et al.* 2005; Liao *et al.* 2008; Chang, Lu 2003; Wright 2005; Dorado *et al.* 2008; Mansour *et al.* 2011).

The depth of the soaked porous plates reached 55 mm. Due to the porous structure and spacing of wavy lamellar plates placed to each other within a distance of 6 mm, the capillary effect of humidifying the packing material takes place. The humidity of the packing material is found using measuring device M0290, the operation principle of which is based on the method for measuring electrical resistance. The interval of calculating humidity varies from 0 to 99.9%, and measurement error is ±0.1%.

1.3. Establishing pH and temperature of the bio-medium

The required pH and temperature of the solution (bio-medium) saturated with biogenic elements were maintained using buffer solutions (Baltrėnas, Zagorskis 2010). pH was found out with reference to LST ISO 10523 standard. To set the necessary temperature and pH, the Mettler Toledo

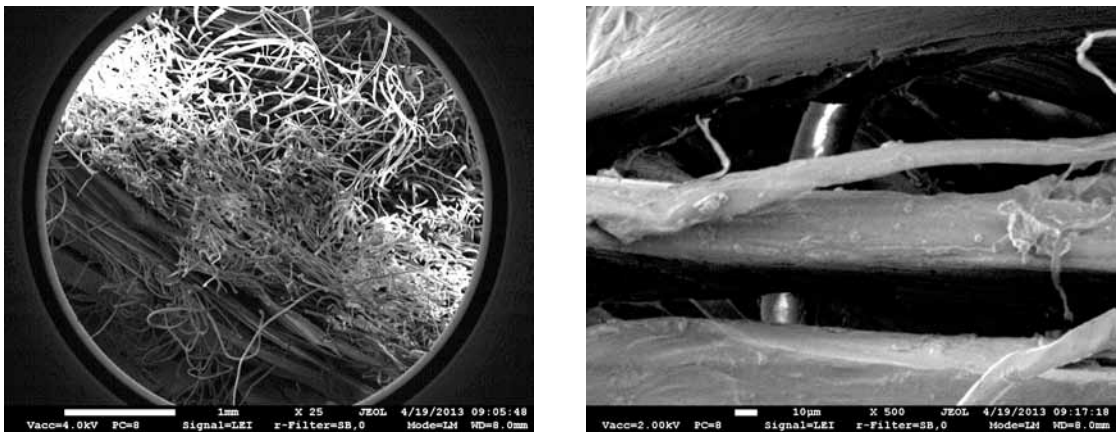

Fig. 3. The structure of not-woven caulking material, magnified 25 times (left) and 500 times (right)

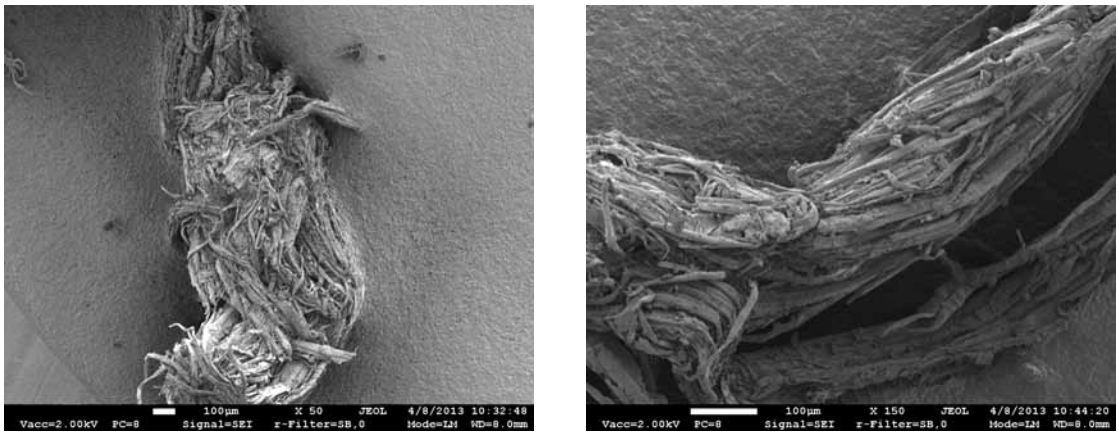

Fig. 4. The structure of birch wood fiber, magnified 50 times (left) and 150 times (right)

measuring device was used. The measurement interval of the device is from 0 to 14, and measurement error is ±0.01. The records of pH index and temperature were displayed on a daily basis.

To preserve a constant temperature of 30 °C in the bio-medium, a heating element of the bio-medium in the lower part of the biofilter was arranged. In order the air supplied to the biofilter should not cool down the bio-medium on the packing material, the duct supplying pollutants has an installed channel heater ensuring a constant 30 °C temperature of the air flow supplied to the biofilter.

1.4. Microbiological research

To identify microorganisms and to calculate their quantity, the flush (suspension dilution) method (presented in the developed methodology) was used. From each sample, 1g-sized piece is weighed and placed in a flask with 90 ml of 0.8% NaCl where suspension procedures take place. To compare different samples with each other, calculations are done drying the specimen material to a constant weight, and then, the number of the microorganisms of 1 g of a dry weight of the biofilter material is defined. In addition, the area of the weighed piece is measured, and the number of microorganisms per 1 cm^2 is calculated.

The composition of the nutrient agar includes water – 1000 g, agar – 15.0 g, peptone – 5.0 g, NaCl – 5.0 g, yeast extract – 5.0 g and meat extract – 1 g. Seeding takes place three times. Under a stagnant medium, the dish moves having a mix of the medium and suspension to make them uniformly spread at the bottom of the dish. At a later stage, Petri dishes, including microorganisms, are incubated in the thermostat.

Petri dishes with bacteria are incubated in the thermostat for 2–3 days and with micromycetes – 5–7 days at a temperature of 26–28 °C. The colonies of micromycetes and bacteria are calculated figuring out the amount of rudiments in 1g of the tested substance. The number of live cells is defined having multiplied the average number of colonies in the dishes and the coefficient of dilution.

Micromycetes were distinguished on the agarized beer wort. Seeds were incubated in Petri dishes under a temperature of +28 °C for 5–7 days.

Pure cultures of micromycetes are identified employing classic methods with reference to the definitions of micromycetes (Chaverri, Samuels 2003; Samson, Frisvad 2004; Domsh *et al.* 2007; Pečiulytė, Bridžiuvienė 2008, etc.).

Yeast were distinguished on the nutrient media of Sabouraud agar with chloramphenicol (Liofilfem, Italy) and Rose Bengal CAF agar (Liofilchem, Italy). Seeds took place in Petri dishes at a temperature of +28 °C for 3–4 days.

Yeast were discovered applying Api 20 C AUX (bioMérieux, France) identification systems.

Bacillus cereus media were agarized. Crop prepared bacterial suspension included 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.

The distinguished bacteria were identified according to their morphological and physiological properties and compared with data provided in literature. Bacteria were described according to Bergey's Manual of Systematic Bacteriology (Palleroni 1984; Garrity *et al.* 2005).

1.5. Activating the packing material and establishing the efficiency of the biodestruction process

The conducted research involved the air flow that passed through the packing material of the biofilter and was contaminated with acetone, xylene and ammonia vapours. The air flow rate between wavy lamellar plates reached, on average, 0,08 m/s and was established and observed on a daily basis applying precision humidity measuring instrument Testo 400 with a thermocouple, the precision of the measurements of which, under the air flow rate from 0 m/s to 2 m/s, makes ±0.01 m/s.

The initial concentration of pollutants reaches, on average, 5.7 mg/m^3. The device was supplied with acetone vapour for 15 minutes 4 times a day. The next day, the concentration of the organic compound was increased 20±5 mg/m^3 thus extending the delivery time of acetone vapour up to 1 hour. The research on supplying the air polluted with acetone vapour took 15 days. Afterwards, the pollutant was replaced with xylene, and investigation was carried on gradually increasing the concentration of acetone vapour delivered to the biofilter. The study on emitting the air polluted with xylene vapour took 5 days. Upon the completion of research on xylene, the air contaminated with ammonia vapours passed through the packing material. Investigation into ammonia lasted for 6 days.

The efficiency of pollutant biodegradation is calculated having found the concentration of the pollutant before and following the treatment device. Pollutant concentration is established with the help of portable VOC monitor MiniRae 2000, the measurement limits of which are in the range from 0 to 7000 mg/m^3. Measurement accuracy, when pollutant concentration is in the range from 0 to 100 mg/m^3, makes 0.1 mg/m^3, and when pollutant concentration exceeds 100 mg/m^3 – 1 mg/m^3.

2. Results and discussion

The biopacking material is one of the basic elements of the biofilter. A crucial point before conducting investigation is the formation of the packing material upon which the physical qualities of the packing material depend and determine the efficiency of the biodegradation process. In this case, the porosity of the packing material and

capillary play a leading role. It has been established that a higher porosity of the material causes better absorption of pollutants from the contaminated air (Beyaz *et al.* 2010). Herewith, a higher porosity of the material makes the capillary humidification of the packing material more effective. Due to a higher porosity of the packing material and effective capillary, the biodegradation process becomes more efficient.

Investigation into the structure of materials has revealed that the major part of not-woven caulking material is made from small filaments of 15 to 25 μm thick. The spaces between the filaments are 5 to 10 times larger than the thickness of the filaments themselves (Fig. 3, left). Such filament distribution allows making a biofilm thus avoiding anaerobic zones harmful to microorganisms. Chaotic filament distribution allows increasing the specific surface area of the material and the volume of the bio-medium in the material. The picture of the material magnified up to 500 times displays the filaments of 120–180 μm thick making the capillaries of 10–30 μm thick (Fig. 3, right). Steam exploded birch fiber also has an irregular surface, porous structure, and thus a higher specific surface area (Fig. 4). As indicated, birch wood fiber is made of like the many tiny "straws" arranged in parallel to each other and reaching 15–30 μm thick. Wood fiber in the packing material is required so that the microorganisms in the biomedia should take up organic carbon that is in the fiber.

Before starting the exploitation of biological air treatment equipment, the installed biopacking material is biologically activated emitting it through the air contaminated with organic pollutants (Baltrėnas *et al.* 2004). The biologically activated packing material is fully accepted as such when covered with a thin layer of the biofilm (5–30 μm thick) with a population of microorganisms. In this case, the packing material was activated up to the 10th day of the experiment. The packing material was activated supplying acetone to the polluted air thus increasing the concentration of acetone and monitoring the treatment efficiency of the biofilter.

Fig. 5 shows that the air treatment efficiency of the biofilter increased up to the 10th day of the experiment. This is exactly the time when the highest established treatment efficiency reached 94.7%, which was caused by a growing amount of bacteria up to $(1.0\pm0.2)\times10^{10}$ cfu/cm^2. The initial acetone concentration before treatment made 25 mg/m^3, whereas at the end of the experiment it reached 700 mg/m^3.

On the 10th day, 220 mg/m^3 acetone vapour concentration was supplied to the biofilter. Under the pollutant concentration of 300 mg/m^3, the air treatment efficiency of the biofilter made 93.4%.

Later, a growth in the amount of pollutant concentration in air up to 500 mg/m^3 reduced the air treatment efficiency of the biofilter to 86%. On the 16th day of the conducted investigations, the concentration of acetone was increased to 700 mg/m^3, which resulted in the treatment efficiency of 84%.

The analysis of the below chart showing the treatment efficiency of acetone demonstrates that, under steady analysis (starting from the 10th day of the experiment), treatment efficiency was higher than 80%.

The average amount of bacteria after the 10th day of research was $(6.8\pm0.2)\times10^8$ cfu/cm^2, yeast – $(3.8\pm0.4)\times10^6$ cfu/cm^2 and micromycetes – $(3.2\pm0.6)\times10^7$ cfu cm^2.

Study was carried out under the treated air flow and made 1.08 l/s. Time for contact between the packing material and the polluted air reached 11.39 s.

A comparison of the research findings of other scientists such as Chang and Lu (2003) who investigated the air contaminated with acetone vapour and the results of our examination demonstrate that treating efficiency reaches from 80% to 85%, and the concentration of acetone vapour in the supplied air makes from 175±10 mg/m^3 to 700±35 mg/m^3. In our case, the treatment efficiency of 80% is available when the concentration of acetone in air gets to ~ 600 mg/m^3.

Fig. 6 shows that treatment efficiency within the biodestruction process of xylene in all days of the performed investigation reached more than 80%. The initial pollutant

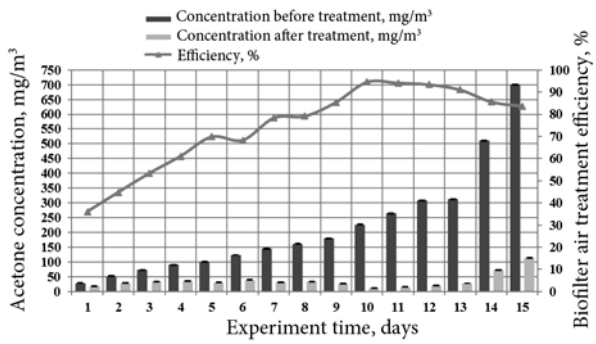

Fig. 5. Acetone concentration before and after treatment (mg/m^3) and the efficiency of biofilter treatment under the application of wavy lamellar plates and the packing material made of wood fiber and not-woven caulking material

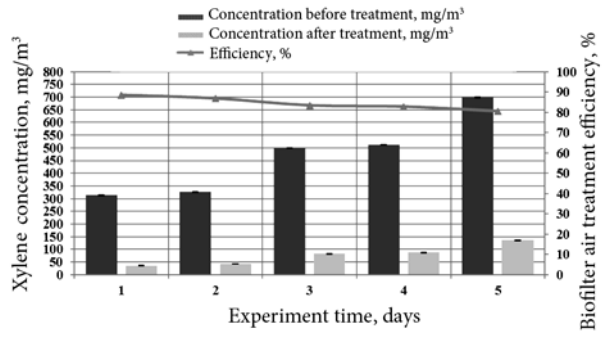

Fig. 6. Xylene concentration before and after treatment (mg/m^3) and the efficiency of biofilter treatment under the application of wavy lamellar plates and the packing material made of wood fiber and not-woven caulking material

concentration before treatment was 313 mg/m^3, whereas at the end of the experiment – 699 mg/m^3. Fig. 6 also demonstrates that the air treatment efficiency of the biofilter, under the pollutant concentration of 300 mg/m^3 (1st day of research), achieved 87.7%, under a concentration of 500 mg/m^3 (3rd day of research) – 83.1% and under a concentration of 700 mg/m^3 (5th day of research) – 80.6%.

An increase in pollutant concentration in the supplied air resulted in a gradual decrease of 3–4% in air treatment. A reduction of microorganisms in the packing material can also be attached to this phenomenon. At the beginning of the research, the average amount of bacteria was (1.8±0.3)×10^9 cfu/cm^2, yeast – (4.1±0.1)×10^6 cfu cm^2 and micromycetes – (1.2±0,6)×10^5 cfu/cm^2, whereas at the end (5th day of research) – (4.6±0.0)×10^8 cfu/cm^2, yeast – (2.2±0.1)×10^5 cfu/cm^2 and micromycetes – (1.4 ± 0.3)×10^6 cfu/cm^2. Japanese scientists Jeong *et. al.* (2008) also investigated the biofilter supplying it with the concentrations of xylene vapour. The obtained results indicate that, under the biofilter productivity of 50 g/m^3/h, treatment efficiency makes 80–85%. Wu *et al.* (2006) studied biofilter treatment efficiency under the device productivity

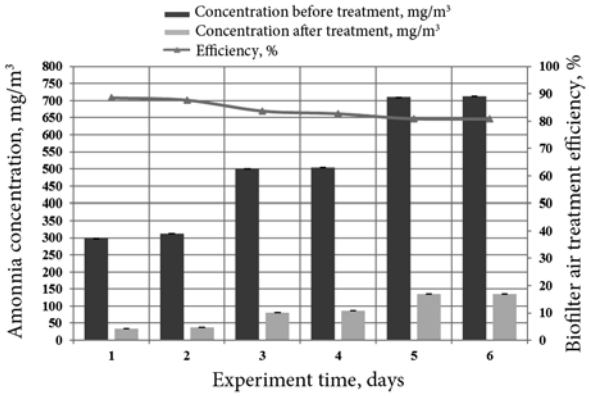

Fig. 7. Ammonia concentration before and after treatment (mg/m^3) and the efficiency of biofilter treatment under the application of wavy lamellar plates and the packing material made of wood fiber and not-woven caulking material

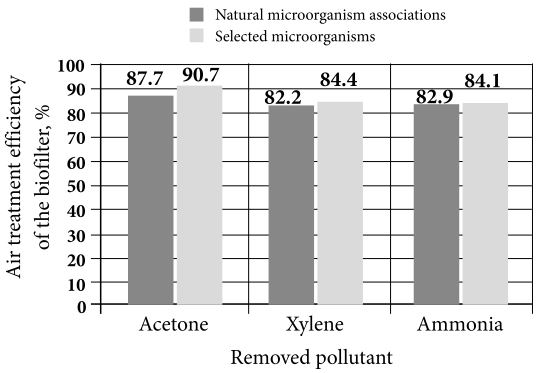

Fig. 8. A comparison of the air treatment efficiency of the biofilter using natural microorganisms and selected microorganisms

of the same 50 g/m^3/h and found out that the biodestruction process of xylene amounted to 70%. As regards our research, under similar productivity of the biofilter, the efficiency of the biodestruction process makes 83%.

While treating the air contaminated with acetone vapour, the efficiency of the biodestruction process was higher than that in the case of xylene vapour. This could be determined by a lower coefficient of gas solubility in water. The dependence of gas solubility in the bio-medium is determined by Henry's Law (Miller, Allen 2005) which provides that, "at a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid". Thus, an increase in temperature decreases gas solubility in the medium while a decrease increases it (Miller, Allen 2004).

Figure 7 displays ammonia concentration in the air supplied to and removed from the device and the dependence of air treatment efficiency on time considering the air flow rate in the packing material (0.079 m/s). The research was carried out under the treated air flow making 1.1 l/s. Time for contact between the biopacking material and polluted air was 11.42 s.

Figure 7 also shows that the treatment efficiency of the ammonia biodestruction process, in all days of investigation, similarly to xylene, reached more than 80%. The air treatment efficiency of the biofilter, under 300 mg/m^3 (1st day of research), in the concentration of ammonia vapour got to 88.1%, the one under 500 mg/m^3 (3rd day of research) – 83.3% and that of 700 mg/m^3 (6th day of research) – 80.9%.

The tendency towards the efficiency of removing ammonia from air, like xylene, remained similar – an increase in the concentration of ammonia in the supplied air resulted in a gradual decrease of 4–5% in the efficiency of taking away the pollutant. This influenced a reduction in microorganisms in the packing material. At the beginning of research, the average amount of bacteria was (7.8± 1.0)×10^8 cfu/cm^2, yeast – (2.6±0.1)×10^7 cfu/cm^2 and micromycetes – (5.6±0.9)×10^6 cfu/cm^2, whereas at the end of research (6th day) – (1.6±0.2)×10^8 cfu/cm^2, yeast – (6.1± 0.2)×10^6 cfu/cm^2 and micromycetes – (2.4±0.2)×10^5 cfu/cm^2. The biopacking material contained the largest established amount of bacteria and the smallest amount of micromycetes.

Figure 8 shows the use of the natural microorganism associations multiplied naturally on the biopacking material from ambient air, which is the reason for achieving a lower air treatment efficiency of the biofilter.

While conducting experimental investigations into wavy lamellar plates and using the packing material made of not-woven caulking material and wood fiber, both the self-propagated and selected microorganisms survived under the same maintained conditions: the average humidity

was from 70 to 80%, the humidity of the packing material made 60–65 %, air temperature reached 26–28 °C and air flow rate – 0.08 m/s. Contact time for the bio-medium remained the same thus making 11.25 s, pH index varied between 7.2 and 7.3 and the temperature of the medium was 30±1 °C. Thus, it can be accepted that the conditions for the development of the self-propagated and selected microorganisms were favourable enough, and therefore the findings of the performed research can be compared with each other.

The presented (Fig. 8) demonstrates that, along the entire investigation, the air treatment efficiency of the biofilter was more than 80%. The conducted research also found that the highest air treatment efficiency was observed using the selected microorganisms, and while treating the air contaminated with acetone vapour, it reached 90.7%. Study on air treatment efficiency under conditions when natural microorganism associations grew and multiplied on the biopacking material suggest the efficiency of 87.7%. Next to acetone, the air contaminated with xylene vapour was supplied to the biofilter, and air treatment efficiency was higher employing the selected microorganisms (84.4%) rather than in the case of the self-propagated ones (82.2%). The research on xylene and supplying the air contaminated with ammonia to the biofilter highlight the same tendency displaying higher air treatment efficiency under the use of the selected microorganisms, which made 84.1%, i.e. 1.2% more than the application of natural microorganism associations.

The species composition of microorganisms also has an impact on the air treatment efficiency of the biofilter. The efficiency of using the microorganisms selected and self-propagated on the packing material is higher, as the microorganisms themselves have been specially selected so that to adopt them to the biopacking material and to the three types of pollutants supplied to the biofilter. Thus, the conducted experimental investigation into air treatment has shown that air treatment efficiency, yet at the beginning of the experiment, reaches approximately 50%, whereas as regards natural microorganism associations, it makes only 50%. In the latter case, various species of the natural microorganism associations multiply on the biopacking material; however, only those able to adapt to the contaminant supplied to the biofilter and to its concentration survive.

The advantage of using the selected microorganisms for removing pollutants from the supplied air is that large concentrations of polluted vapours can be supplied to the biofilter, because the selected microorganisms unlike the self-propagated ones do not require adaptation, and therefore air treatment efficiency is higher.

The conducted research has demonstrated that acetone and ammonia rather than xylene are best removed from the contaminated air. This is due to the fact that acetone and ammonia are highly soluble in water, whereas xylene is not. For their growth, microorganisms on the biopacking material absorb airborne pollutants through water. Therefore, microorganisms easier absorb ammonia and acetone rather than xylene, which allows making a conclusion that the higher is the solubility of the pollutant in water, the greater is treatment efficiency.

Conclusions

The conducted research has shown that the use of the capillary system for the humidification of the packing material made of porous polymer wavy lamellar plates with wood fiber and not-woven caulking material results in the air treatment efficiency of the biofilter, which is more than 80%.

The performed investigation demonstrates that the highest air treatment efficiency has been achieved employing the selected microorganisms. While treating the air contaminated with acetone vapour, efficiency reached 90.7%, xylene made 84.4% and ammonia – 84.1%. The average use of the selected microorganisms points to air treatment efficiency which is 2.4% higher than that employing natural microorganism associations.

Experimental investigation into the selected microorganisms applied for air treatment has revealed that air treatment efficiency, yet at the beginning of research, achieves about 50%, whereas in the case of the self-propagated ones, only 50% can be observed. In the latter case, various species of natural microorganism associations multiply on the biopacking material; however, only those able to adapt to the contaminant supplied to the biofilter and to its concentration survive.

The carried out research has established that acetone and ammonia rather than xylene are best removed from the contaminated air. This is due to the fact that acetone and ammonia are highly soluble in water, whereas xylene is not.

Bacteria – $(1.0\pm0.2)\times10^{10}$ cfu/cm^2, yeast – $(6.1\pm0.2)\times10^{6}$ cfu/cm^2 and micromycetes – $(3.2\pm0.6)\times10^{7}$ cfu/cm^2 are among the cultures most frequently found between the selected microorganisms of the biopacking material.

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