AERATION EQUIPMENT FOR BUBBLELESS AERATION WITH PARTIAL AUTONOMOUS REGIME FOR SMALL DEPTHS OF WATER COLUMN

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Outbreak of cyanobacteria can cause problems with water quality in summer months. Cyanobacteria is a bacterium that produces poison called cyanotoxin. When the concentration of cyanobacteria increases, the phenomenon „algal bloom“ appears, which is very toxic and may kill all the organisms. The ecological reduction of growth of cyanobacteria is carried out by aeration of water. The mechanic and pneumatic aerators are very often used but these equipments are not cost-effective and have a high consumption of electricity. This article is focused on potential more cost-effective aeration via hollow fibre membrane. This technology is bubbleless and almost all oxygen delivered is dissolved on the membrane. First part of the article is focused on measurement in the laboratory and testing of modules with hollow fibre. Second part is focused on the distribution of disolved oxygen in the whole reservoir with small depths which is ensured by a small partly autonomous boat.

KEYWORDS

Aeration, destratification, diffusion, hollow fibre, autonomous equipment, cynobacteria

1 INTRODUCTION

Fresh water is a strategic raw material that is essential for the living on the Earth. Quality of fresh water resources is decreasing from year to year and the governments are taking protection measures to protect them. The article is focused on lentic type of water formations such as reservoirs, dams and ponds. The quality of water in those reservoirs is tested mainly in summer months when it is changing very fast due to temperature changes. The quality of water is being affected by many factors. The main factors are temperature, amount of dissolved oxygen (DO), presence of cyanobacteria and other photosynthetic organisms. The dissolved oxygen is vital for living in aquatic ecosystem. The dissolved oxygen in lentic type of water is consumed by water organisms, by sediment oxidation and by respiration of phytoplankton. The phytoplankton transforms carbon dioxide into oxygen in the daylight but photosynthesis doesn't work without light energy. The phytoplankton uses oxygen for respiration and it produces carbon dioxide when the water surface is covered and during the night. If biodiversity is preserved the situation in aquatic ecosystem is good, as well as water quality. The outbreak of one kind of organism may disturb the biodiversity. The outbreak of cyanobacteria is frequently happening in water where the sediment contains mineral elements namely compounds of phosphor and compounds of nitrogen. This is breeding ground for cyanobacteria and of course other photosynthetic organisms. The population of cyanobacteria gradually covers the whole water surface. When the population of cyanobacteria is covering the whole surface, the phenomenon „algal bloom“ appears, which is very toxic and may kill all the organisms. The algal bloom causes two types of problems. First, cyanobacteria which covers the surface is producing oxygen during the daylight. Other phytoplankton is overshadowed by the algal bloom from the light and it uses the oxygen for respiration. The amount of dissolved oxygen is acceptable during the daylight but it decreases during the night. In early morning the amount of dissolved oxygen is almost zero. Secondly, cyanobacteria produce cyanotoxin. It is a poison which cyanobacteria use for delimitation of their teritory and it is very toxic for all organisms. More about cyanotoxins is stated in [Gregor 2004]. For example cyanobacteria caused fish mortality in aquaculture pond in Bangladesh [Jewel 2003], Turkey [Tas 2006] and many others.

Cyanobacteria population can be reduced by chemical means, biological methods, physical methods or mechanical methods. The chemical means which contain compounds of aluminium or iron are based on reduction of phosphorus compounds. Their function is flocculation and collagulation. The review of chemical means for reduction of cyanobacteria is mentioned in [Jancula 2011]. The biological methods are based on establishing of the biodiversity. The equilibrium is quite fragile and one organism usually dominates.

The cyanobacteria use the gas vacuoles which allow movement through the water column. It is a big advantage compared to alga. Physical methods are based on the destruction of gas vacuoles or the rupture of cyanobacteria colonies. Methods use effect of ultrasound, cavitation or UV radiation. [Jancula 2014]

Mechanical methods are based on removal of cyanobacteria by filtration, aeration of water or destratification of water. For the removal of cyanobacteria by filtration the special boat with filtration arm is used. This boat is collecting the phytoplankton from water surface. Aeration described by [Marsalek 2004] is ecological and preventive method. The principle of this method is supply of the oxygen into the water near the bottom where the sediment containing mineral elements oxidizes. The water is aerated and the oxygen is dissolved in entire volume of water column. This method is based on the removal of the advantage of cyanobacteries (given by gas vacuoles) and the support of grow of the other phytoplankton in reservoir. The typical mechanical aerator consists of impeller, motor and platform. Impeller rotation is delivering the air under the water surface. The efficiency of oxygen transfer is around 10 % and the electricity consumption is high. The comparison of typical mechanical aerators is provided by [Boyd 1998].

Next type of mechanical aerator is pneumatic aerator which is based on injecting of the air into the aeration elements which generate small bubbles. The bubbles are dissolved into the water and slowly go up to the water surface. Efficiency of oxygen transfer is 30 % but it highly depends on depth of the reservoir.

This article is focused on testing of membrane module which carries out bubbleless aeration with efficiency of oxygen transfer approaching 90 %. This technology for aeration of water has a potential to be more cost-effective than current technologies.

Next part of the article is focused on partly autonomous boat which is equipped by frame with membrane and designed for aeration of reservoir. The boat is in accordance with Industry 4.0

2 BACKGROUND OF OXYGEN TRANSFER

The kinetics of oxygen transport during aeration can be described by differential equation (see [Boyd 1998])

$$V\frac{dC}{dt} = K \cdot S \cdot (C^* - C) \quad (1)$$

where V is volume of aerated water (m^3), t is time (hr), K is overall mass transfer coefficient (m.hr^{-1}), S is the interfacial contact area (m^2), C^* is DO concentration at saturation (g.m^{-3})and C is the measured concentration of DO in water (g.m^{-3}).

The values of DO concentration at saturation and at particular water temperature can be calculated from second formulation of Henry's law. This formula states that the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid P (Pa). The Henry's constant H_C (Pa.m^3.g^{-1}) depends on temperature and increases with increasing temperature. The Henry's constant for dissolving oxygen in water for various temperatures is given in [Rettich 2000].

$$C^* = \frac{P}{H_C} \quad (2)$$

Equation (1) is derived for transfer of oxygen only through aeration element. If the aeration element is used in reservoir with open surfaces, it is necessary to rewrite the equation (1) to include surface aeration.

$$V\frac{dC}{dt} = K \cdot S \cdot (C^* - C) + K_H \cdot S_H \cdot (C^*_{atm} - C) \quad (3)$$

where C^*_{atm} is dissolved oxygen concentration in equilibrium with partial pressure of oxygen in air (g.m^{-3}), K_H is the exchange coefficient at the gas–liquid interface(m.hr^{-1}) and S_H is the effective surface area for gas–liquid exchange (m^2).

Rearranging and solving (1) leads to equation (4) which is valid for aeration without open surface where C_0 is dissolved oxygen concentration for time t = 0, C is dissolved oxygen concentration for time t.

$$ln\left(\frac{C^* - C_0}{C^* - C}\right) = \frac{K \cdot S \cdot t}{V} \quad (4)$$

Solving (3) with the same boundary condition as for (1) gives (5) which is valid for aeration with open surface

$$ln\left(\frac{C - F}{C_0 - F}\right) = -\frac{t}{V}(K \cdot S + K_H \cdot S_H) \quad (5)$$

where F is defined by

$$F = \frac{(K \cdot S \cdot C^* + K_H \cdot S_H \cdot C^*_{atm})}{K \cdot S + K_H \cdot S_H} \quad (6)$$

The exchange coefficient at the gas–liquid interface K_H is difficult to be estimated theoretically. It is determined by experiment.

This approach is useful only if it is possible to determine the interfacial contact area. Determining the interfacial contact area for mechanical, pneumatic or hydropneumatic aeration is practically impossible. In these cases, the ratio of the interfacial contact area to the volume of aerated water is used. This ratio α (m^{-1}) is given by

$$\alpha = \frac{S}{V} \quad (7)$$

By inserting of equation (7) into equation (1), we obtain

$$\frac{dC}{dt} = K \cdot \alpha \cdot (C^* - C) \quad (8)$$

where product $K.\alpha$ (hr^{-1}) is called the oxygen transfer.

The oxygen-transfer coefficient is adjusted to 20°C with the following equation

$$K_{20} \cdot \alpha = \frac{K \cdot \alpha}{1.024^{T-20}} \quad (9)$$

where $K_{20}.\alpha$ (hr^{-1}) is the oxygen transfer coefficient at 20°C and T (°C) is water temperature.

3 EXPERIMENT

3.1 Membrane module characteristics

Microporous polypropylene hollow fibre membrane P60 was used in experiments. The membrane is manufactured by Zena Membranes. The membranes have an outer diameter of 310 μm, inter diameter of 240 μm and mean pore size of 0.1 μm. The fibre collapse pressure is higher than 3.5 bars.
Tested membrane module consists of five bundles and each bundle contains 1350 fibres. The area of the membrane module is 2.83 m^2.

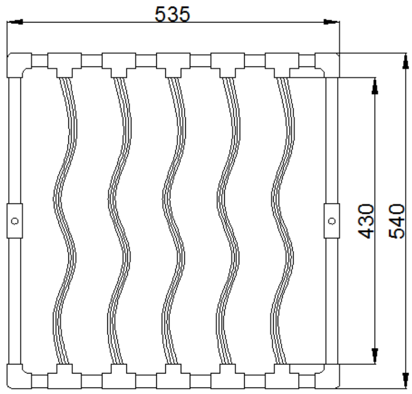

Figure 1. Aeration module with dimensions

3.2 Test rig

Test rig consists of a pneumatic circuit and an aeration module located in the bottom of the tank. The volume of the tank is *500* dm^3 and is filled with tap water. The pneumatic circuit ensures compressed air supply to the membrane module. The compressed air for the experiment was provided from an air supply in the laboratory. The compressed air was filtered in order to avoid the pores becoming clogged by impurities. The value of the air pressure in the aeration module is adjusted by pressure regulator which also contains pressure gauge. Amount of air which flows into the membrane is measured by gas meter.

Scheme of the test rig is shown in the Fig. 2.

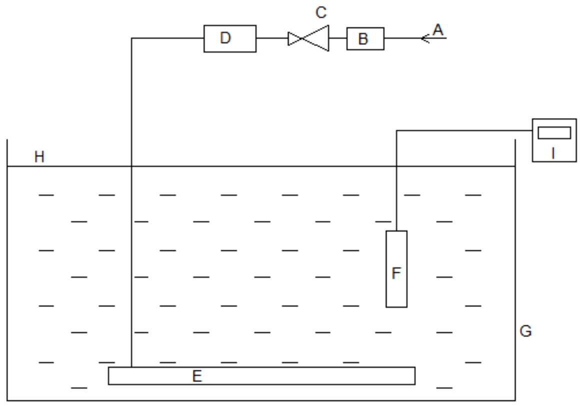

Figure 2. Scheme of the test rig

where A – compressed air supply, B – air filter, C - pressure regulator with manometer, D – gas-meter, E – aeration module, F – DO probe, G – tank, H – surface cover, I - display.

3.3 Testing procedure

The essence of the experiment is to carry out the aeration with wet pores (i.e. pores filled with water) in order to avoid generating of bubbles but rather to dissolve the oxygen in the water. Filling of the pore directly with water is not possible and therefore the membrane was first filled with pure industrial alcohol. The membrane was immersed into pure industrial alcohol for 1 hour and then filled with pure water.

The experiment was carried out with tap water which cotains large amount of dissolved oxygen. Before the start of the experiment the water was deoxygenated with cobalt chloride and sodium sulfite. Cobalt catalyzes the reaction between molecular oxygen and sodium sulfite.

The aeration module was placed on the bottom of the tank and loaded to avoid changing of the position due to buoyant force. The compressed air was delivered into the aeration element and the aeration started. The value of current amount of dissolved oxygen in the water and water temperature over time was recorded during the whole experiment. The experiment was terminated after reaching of defined oxygen saturation point or after expiry of defined period. The experiment was carried out for three pressure configurations, namely 1 bar, 1.5 bar and 2 bars.

3.4 Results

The mass transfer coefficient *K* is used for comparison of individual aeration modules. Equation (4) will be used to determine the coefficient because the surface of water is covered. To calculate the coefficient it is necessary to know DO concentration at saturation and at particular water temperature C^* (mg.L^{-1}). These values can be calculated according to equation (see [Ros 2002])

$$C^* = 14.6 - 0.3943 \cdot T + 0.007714 \cdot T^2 - 0.0000646 \cdot T^3 \qquad (10)$$

From linear regression referred to in Fig. 3 is the coefficient Kα = 0.1881 hr^{-1} for the pressure 1.0 bar, Kα = 0.3397 hr^{-1} for the pressure 1.5 bar and Kα = 0.5134 hr^{-1} for the pressure 2.0 bar. According to equation (9) the coefficient Kα is recalculated for 20°C. The temperature inserted into the equation corresponds to the average temperature of the water during the experiment t = 19.69°C for the pressure 1.0 bar, t = 19.00°C for the pressure 1.5 bar and t = 18.30°C for the pressure 2.0 bar.

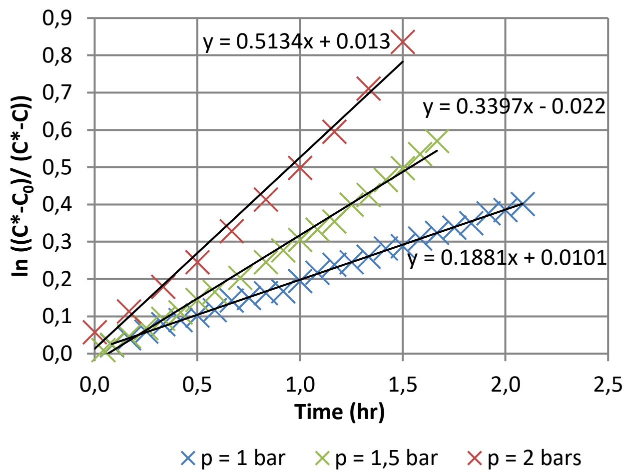

Figure 3. Evaluation of coefficient Kα

From the equation (7) and from known area of the membrane S = 2.83 m^2 and the volume of aerated water *V = 458* L coefficient *K* can be calculated. For the first configuration (pressure 1.0 bar) K = 0.0307 mhr^{-1}, for the second configuration (pressure 1.5 bars) K = 0.0563 mhr^{-1} and for the third configuration (pressure 2.0 bars) K = 0.0865 mhr^{-1}.

Determination of the efficiency η (%) of oxygen use shall be carried out on the basis of the equation (11), where C_t (mg.L^{-1}) is amount of dissolved oxygen in water in time *t*, C_0 (mg.L^{-1}) is amount of dissolved oxygen in time t_0, *V* (L) is volume of aerated water and m_{O2} (mg) is amount of delivered oxygen.

$$\eta = \frac{(C_t - C_0) \cdot V}{m_{O2}} \cdot (100)\% \qquad (11)$$

The efficiency of transport of the oxygen into the water for the first configuration achieved 86.47 %, for the second configuration 85.39 % and for the third configuration 87.86 %.

4 DESIGN OF AERATION EQUIPMENT

Equipment is designed as a float partly autonomous mobile aeration unit which can be used in standing water with small depth, see Fig. 4. It consists of supporting module, aeration module and control unit.

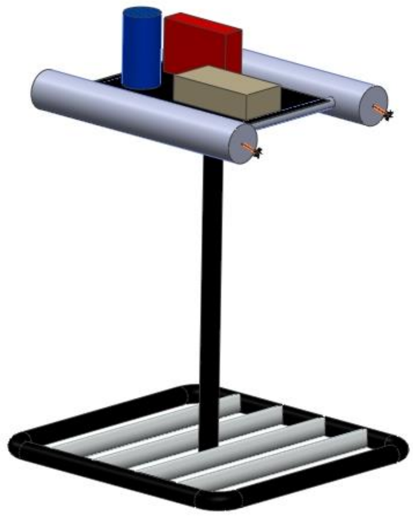

Figure 4. Design of aeration equipment

4.1 Supporting module

Supporting module consists of two floats with a diameter of 125 mm and a length of 600 mm. The platform with control unit is located on the upper side of the floats. The aeration module is firmly connected to the platform. Movement is provided by two electric motors located at the end of floats. The motors are connected to propellers via shaft with clutch. The movement is provided by one right-handed propeller and one left-handed propeller to eliminate forces into direction control. The propellers include two blades and the maximal power of each motor is 10 W.

4.2 Aeration module

Aeration module consists of compressor, gas accumulator, pressure probe, pressure regulator, connection pipe and last but not least aeration element. For the scheme see Fig. 5.

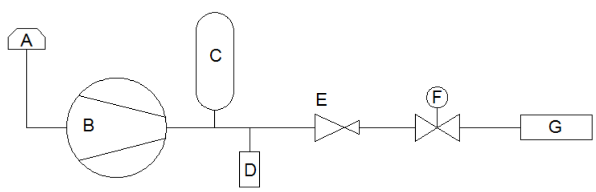

Figure 5. Scheme of aeration module

where A - suction, B - compressor, C - gas accumulator, D - pressure probe, E - pressure regulator, F - electric valve, G - aeration element.

The air is sucked by compressor via filter. The power of compressor is 42 W and the pressure range of supply air into aeration element is up to 3.5 bars. The air is storaged in gas accumulator with the volume of 2 dm^3. The gas accumulator with pressure regulator also contributes to stabilising pressure fluctuations. The aeration element is the same as in laboratory experiments.

4.3 Control unit

The heart of control unit is programming board Arduino Mega 2560 with microcontroller ATmega 2560 manufactured by Atmel. All components and probes are connected into board, see scheme Fig.6.

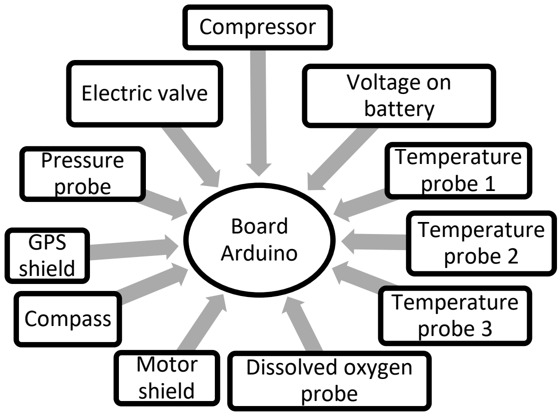

Figure 6. Scheme of control unit

The direction and speed of the boat is set by pair of motors which is controlled by H-bridge. The control unit uses pulse width modulation for change of the power of motor via motor shield.

GPS module enables to determine exact position on the Earth. For the purpose of determining of the position in an area it is necessary to accept signal at least from four satellites. Signal from the satellite contains identification of the satellite and time mark. The first found signal shall perform synchronization of time of the GPS system and electronic receiver. The signals from another at least three satellites shall serve to electronic receiver to calculate the distances of the positions of the satellites from electronic receiver.

The use of GPS module to determine azimuth of aeration equipment has disadvantage if the equipment is not permanently in motion because azimuth determined from GPS coordinates is determined as a vector from three consecutive coordinates. Determination of the azimuth by test aerator was carried out by electronic compass which used anisotropic magnetoresistant sensor.

The test aerator was equipped with a probe for measurement of dissolved oxygen on galvanic basis. The probe is able to detect dissolved oxygen in the range of (0 – 20) $mg.L^{-1}$ in the temperature range (0 – 40)°C.

The air temperature, water temperature around aeration element and the temperature at the surface of the water were monitored using temperature sensor. Pressure sensor on the test aeration module serves to switching on and off of the compressor. Energy for the whole equipment is provided from gel battery.

4.4 Programs

Control program is written in Wiring language and is loaded on the base plate. Control program of the aerator is divided in part controlling the aeration, part controlling the movement of the aerator and part for recording of the values.

Control program which operates aeration process measures value of the pressure in pneumatic circuit using pressure sensor. Measured value of the pressure is compared with the limit adjusted for aeration and the compressor is then switched on or off.

The program for recording of the values records in regular 5 seconds interval the data from the sensors and the status of the system controls on SD card.

Program for control of the aerator in autonomous mode controls engine module so that aerator moves between adjusted points. Current position of the aerator is identified using GPS module. Geographic coordinates are latitude and longitude. Partial elimination of error of GPS position due to inaccuracy of GPS module is carried out by averaging of found geographic coordinates.

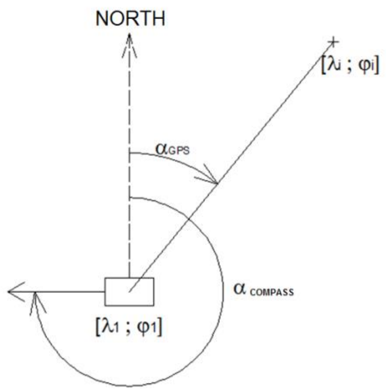

Figure 7. Control of the direction - sketch

Current rotation of aerator considering cardinal direction (azimuth) $\alpha_{compass}$ is calculated from measured magnetic forces in electronic compass. Calculation of azimuth is carried out according to the equation

$$\alpha_{compass} = \operatorname{atan2}\left(\frac{magnetic\ force\ in\ axis\ y}{magentic\ force\ in\ axis\ x}\right) \tag{12}$$

The function atan2 is used in the programming languanges for calculating the arc tangens, because this function is defined for all angles.

Control of the direction is carried out by increase or decrease of power of individual engines so that the difference between azimuth determined by the compass and azimuth received from geographic coordinates of current position of the aerator and position of the nodal point α_{GPS} meets the condition

$$(\alpha_{compass} - \alpha_{GPS}) \in \langle -5°; 5° \rangle \tag{13}$$

The determination of the azimuth from geographic coordinates on irregular surface like Earth would be very difficult, therefore it was necessary to approximate this shape. For above mentioned application where the distance between transfer points are tens to hundreds meters approximation to sphere is sufficient. Azimuth can be calculated according to the equation

$$\alpha_{GPS} = \operatorname{atan2}\left(\frac{\sin\Delta\lambda \cdot \cos\varphi_2}{\cos\varphi_1 \cdot \sin\varphi_i - \sin\varphi_1 \cdot \cos\varphi_i \cdot \cos\Delta\lambda}\right) \tag{14}$$

Where λ_1 is longitude of the aerator, λ_i is longitude of *i*-th nodal point, φ_1 is latitude of the aerator, φ_i is latitude of *i*-th nodal point and $\Delta\lambda$ is difference of longitudes of the aerator and *i*-th nodal point.

On the basis of comparison of azimuth from geographic coordinates and azimuth from the compass change of the ratio of engine power is carried out. Accuracy of determination of the location using coordinates received from GPS module is approximately ±2.5 meters. Consequently precise conformity of geographical cordinates from GPS module by arrival to the nodal point cannot be expected. The control system regularly detects the distance between aerator and nodal point. If the distance decreases to less than 2.5 meters next nodal point is loaded. For determnation of the distance between two points from geographical coordinates the Harvesine equation is used.

4.5 *Testing of autonomous movement system on pond*

The autonomous movement system was tested on a pond U Mlyna in Brno. The length of the pond is 160 m and the width 50 m. The nodal points were selected manually approximately 30 meters apart. All GPS positions from the movement of the boat were visualized on the Fig.8 as well as nodal points.

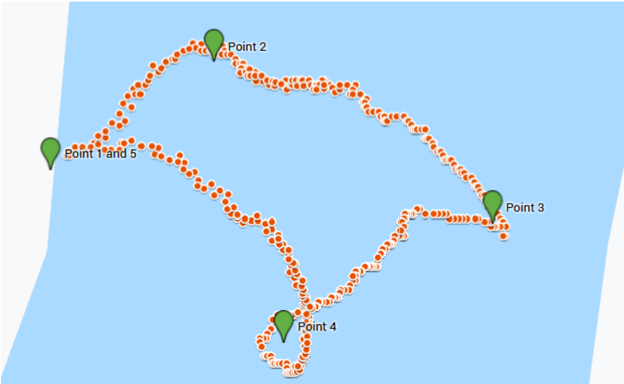

Figure 8. GPS position during the test

The autonomous system transited through all defines points with expected deviation. The deviation is caused by the inaccuracy of the GPS positioning system and the algorithm of control unit. Maximum deviation 3 m from ideal line joining two nodal points is in accordance with the expected accuracy. For the aeration unit during the testing on the pond see Fig.9.

Figure 9. Aeration unit during test

5 CONCLUSION

The article is focused on aeration of water reservoirs with low depth of water column. During summer season aeration of water reservoirs prevents growth of cyanobacteria and it provides oxygen to aquatic ecosystem throughout the year. This is essentially an ecological method which supports biodiversity and it does not deliver chemical pollutants into the water.

Technology of aeration of water reservoirs is currently using mechanical, pneumatic and hydrodynamic aerators. All of above mentioned technologies are very energy intensive and the efficiency of transport of the oxygen into the water is relatively low. Using of the membrane technology, especially membranes consisting of hollow fibres, has a potential for low-energy solution with high efficiency of transport of the oxygen into the water.

Tested aeration module uses a membrane consisting of polypropylene hollow fibres with wet pores. The membrane pores were filled with water which leads to pure diffusion without generating of bubbles. The experiment was carried out in three configurations. In the first configuration the air pressure in the membrane was 1.0 bar, in the second configuration 1.5 bar and in the third configuration 2.0 bars. From the measured dependence of quantity of dissolved oxygen on time the mass transfer coefficient K was calculated, which for the first configuration (pressure 1.0 bar) is K = 0.0307 mhr^{-1}, for the second configuration (pressure 1.5 bars) K = 0.0563 mhr^{-1} and for the third configuration (pressure 2.0 bars) K = 0.0865 mhr^{-1}. The efficiency of transport of the oxygen into the water for the first configuration achieved 86.47 %, for the second configuration 85.39 % and for the third configuration 87.86 %. The difference between the measured efficiency and a perfect efficiency of 100 % could arise from small leakage of pneumatic circuit, inaccuracy of deduction of the values or inaccuracy of the gauges. Nevertheless, the above mentioned efficiency of the input is very good.

The last point of the article is design of aeration equipment with partially autonomous control. For aeration in water reservoir special aeration equipment was designed. This aeration equipment is moving on the water surface and the technology for aeration is installed on the upper deck. The aeration is carried out by membrane aeration module with hollow fibres situated in the water. The movement of the equipment is partially ensured by autonomous control using GPS. The control system was tested on a pond in Brno. The result is the recording from the GPS which shows that aeration equipment is able to operate in automatic mode and it reached all adjusted nodal points within given tolerance. From the recording of the movement of the boat can be seen that there was slight deviation from ideal axis between nodal points. This deviation was caused by inaccuracy of GPS module and by control which works step by step. For the purposes of this application the accuracy of the control is sufficient.

Future work will be focused on determination of influence of shape of bundles, length of fibres and contact the fibres between each other on mass transfer coefficient.

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