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CAPACITY OF TEXTILE FILTERS FOR WASTEWATER TREATMENT AT CHANGEABLE WASTEWATER LEVEL – A HYDRAULIC MODEL

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Abstract: The aim of the study was to describe in a mathematical manner the hydraulic capacity of textile filters for wastewater treatment at changeable wastewater levels during a period between consecutive doses, taking into consideration the decisive factors for flow-conditions of filtering media. Highly changeable and slightly changeable flow-conditions tests were performed on reactors equipped with non-woven geo-textile filters. Hydraulic conductivity of filter material coupons was determined. The dry mass covering the surface and contained in internal space of filtering material was then indicated and a mathematical model was elaborated. Flow characteristics during the highly changeable flow-condition test were sensitivity to differentiated values of hydraulic conductivity in horizontal zones of filtering layer. During the slightly changeable flow-conditions experiment the differences in permeability and hydraulic conductivity of different filter (horizontal zones) height regions were much smaller. The proposed modelling approach in spite of its simplicity provides a satisfactory agreement with empirical data and therefore enables to simulate the hydraulic capacity of vertically oriented textile filters. The mathematical model reflects the significant impact of the filter characteristics (textile permeability at different filter height) and operational conditions (dosing frequency) on the textile filters hydraulic capacity.

Keywords: hydraulic capacity; hydraulic conductivity; septic tank effluent; textile filters for wastewater treatment

INTRODUCTION

Geo-textiles are very common in civil engineering infrastructure [Koerner 2005]. They are manufactured mainly to separate soils from other types of soils or other media and constructions. A very common application of geo-textiles is the protection of the mechanical structure and integrity of the soil being drained [Yaman et al. 2006].

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There are many factors and conditions related to non-woven geo-textile hydraulic conductivity and clogging. Some of these are well known: fibre density [Marks 1975], filtered suspension particle size [Gourc and Faure 1990] and organic material growth or deposition [Hoogerdendorn and Van der Meulen 1977].

The studies conducted thus far [Spychała et al. 2013] showed a satisfactory pollution removal by textile filters for wastewater treatment (TFWT).The average values of removal efficiencies can seem to be relatively low, however much higher values were observed occasionally under slightly changeable conditions (inflow concentrations): up to 89% for COD, 80% for ammonium nitrogen and up to 48% for total phosphorus. Taking into consideration that this type of filter operates without forced (energy consuming) aeration and sophisticated solutions are not applied, it can be considered as satisfactory in its performance.

TFTW hydraulic conditions are complex due to the dosing regimen related to changeable wastewater surface level (which causes changeable hydrostatic pressure). Another flow-related condition is the stratification of biomass (the mixture of live organisms and solids originated from wastewater) concentration and their resistance along the filter layer height (filtering surface is oriented vertically) due to the clogging process. However it is worth noting that the TFWT is a specific filtering medium operating under specific conditions and therefore both internal clogging and surface accumulation (in the form of filter cake) occurs.

The form of biomass inside the textile filter was characterized by some authors [Yaman et al. 2006] as specific – discontinuous bio-grains (not continuous layer of biomass – biofilm). The form of biomass inside the geo-textile can be observed in a light microscope or shown on SEM images (e.g. Abou-Elela et al. [2013]. The analyses of biomass inside the non-woven geo-textile are complicated due to the high moisture of biomass and its high flexibility geo-textile. Therefore the most valuable information can be derived using several techniques and procedures coupled together [Anderson 2009]. However the most common method is still a light microscopic examination. One of the first specific methods for the description of biological growth that resulted in geo-textile clogging was proposed by Mlynarek et al. [1990].

One of the most probable clogging scenarios could be the accumulation of the coarser particles of suspension on the textile surface, forming a network trapping smaller particles [Fluet and Luettish 1993]. This effect was observed during another experiment related to short-term non-woven geo-textile clogging by septic tank effluent [Fluet and Luettish 1993]. The acceleration of clogging process rising and decreasing in flow velocity was observed after a particular period of time and then full clogging was observed. This experiment showed a very high percentage of small particles in septic tank effluent.

The concentration in cross-sectional profile of filtering different thickness layers was described in detail in other papers [Spychała and Łucyk 2015, Spychała and Sowińska 2015].

Both suspended solids and live biomass (resulting from microbial growth) are suggested to be the causes of clogging process intensification [Koerner and Koerner 1990].

The geo-textiles in question can be characterised by several properties. One of the most useful is the opening size, which provides important information related to clogging resistance and filtration properties. However, due to the complex flow, clogging factors and conditions, two geo-textile types with the same opening average size value can exhibit different hydraulic behaviour [Bhatia et al. 1991]. Another important feature of geo-textiles is pore size distribution, which can be determined by image analysis [Merkus 2009].

Some fractions of particles, especially of small diameter, might find their way into the geo-textile inner voids, which can cause a significant decrease in hydraulic conductivity and volumetric flow [Wilson-Fahmy et al. 1996].

The modelling of flow through the filter cake and flow through the porous material e.g. geo-textile filled with biomass of specific form of bio-granules is complex. Due to the numerous conditions and parameters (anisotropic orientation of fibres, heterogeneous content of the filter cake, changeability of biomass according to concentration and form (e.g. bio-granules diameter) in cross-sectional profile of filtering layer many simplifications of mathematical description could be necessary.

Most theoretical studies on porous media (e.g. the filter cake) flow modelling have used spheres as a model aggregate. The permeability of filters is often described as a function of diameter and volume fraction of particles or channels [Kim and Russel 1985, Jackson and James 1986]. Geo-textile flow-conditions have been studied both theoretically and experimentally (considering mostly the decisive parameters like porosity and pore size distribution) by many authors both in plane and normal to the plane [El-Gamal and El-Shafey 2000, Jeon et al. 2004, Narejo 2005, Hufenus and Schrade 2006]. The basic modelling approach to the flow through the geo-textile corresponds to the saturated liquid flow. The first semi-empirical equation of the pressure difference proposed by Kozeny-Carman was modified in 1985 by Kay and Nedderman [1985] with respect to non-woven media. However, this equation is utilizable for porosity to 88%. Above this value the parallel to the flow channel (Kozeny-Carman assumption) is no longer appropriate. Hydraulic conductivity for both the non-woven fabric and filter cake, assuming the form of a fibre, can be calculated from the equation reported by Mlynarek et al. [1994]. The most common assumption is treating the porous medium as a set of channels of an equal or varying cross-sectional area, but of a certain length [Lawrence and Shen 2000]. Kozeny proposed a model of laminar flow by parallel capillary cross-sectional areas perpendicular to the flow direction, wherein the designation of the area requires knowledge of the shape, size and packing composition of filter material.

In 1956 Carman modified Kozeny's equation by the introduction of the surface area in respect to the particles constituent [Lawrence and Shen 2000]. Kozeny's constant has also been modified by the introduction of shape factor and tortuosity factor. Since the Kozeny-Carman equation describes the general relationship between porous media permeability and its geometric structure, some authors looked for the possibility of applying this equation to fibrous structures by introducing a different shape factor value or formula [Rushton and Green 1968].

There are many other known approaches to the mathematical modelling of flow (permeability) through the geo-textile [Lord 1956, Giroud 1996]. The relatively new approaches to flow through the textile media consist of a three-dimensional structure description using fractal aggregates [Kim and Stolzenbach 2002].

The aim of the study was to describe the hydraulic capacity of textile filters for wastewater treatment at changeable wastewater levels during a period between consecutive doses, taking into consideration the decisive factors for flow-conditions of filtering media (hydraulic conductivity determined by the biomass concentration, biomass particles diameter and effective porosity) as a mathematical model. It was assumed as a hypothesis that hydraulic conductivity value and initial wastewater surface level can be an appropriate modelling parameters for process description.

MATERIALS AND METHODS

Highly changeable flow-conditions experiment

The first stage of research (highly changeable flow-conditions experiment at high changes in wastewater surface level) was performed in a period between 01.2013 and 06.2014 on the reactor equipped with four filters of a thickness of 3.6 mm, which consisted of four layers of non-woven TS 20 geo-textile of 0.9 mm thickness. The reactor was supplied with septic tank effluent six times per day. The wastewater volume per loading was 750–800 cm^3 and the organic loading rate was between 0.04 and 0.2 mg BOD_5/(mg DM · d). The duration of a single loading was four hours. Due to the intermittent dosing the reactors operated at changeable wastewater surface levels.

The basic facilities of a needle-punched polypropylene continuous fibre non-woven geo-textile TS 20 are: surface mass – 125 $g \cdot m^{-2}$, opening size O_{90} – 0.105 mm and permeability – 115 $dm^3 \cdot (m^2 \cdot s)^{-1}$.

The research reactors are presented in figure 1. Construction of similar filters was described in previous papers [Spychała et al. 2013]. Domestic wastewater from a one-family household was pre-treated in a septic tank and then filtered under hydrostatic pressure.

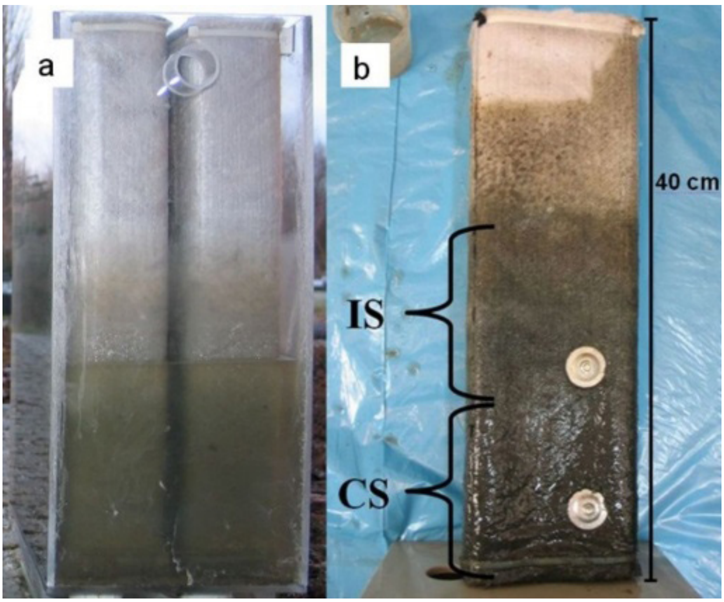

Fig. 1. Research reactor – front view (a), continuously (CS) and intermittently (IS) saturated regions of filter (b)

The reactors were supplied with septic tank effluent at a dose volume resulting in an initial wastewater surface level about 33 cm of filter height.

The contamination indicators of inflowing wastewater from the period 01.2013–06.2014 were: BOD_5: 290 ± 33 g · m^{-3}, COD: 519 ± 30 g · m^{-3}, ammonium nitrogen: 114 ± 4 g · m^{-3}, total phosphorus: 17 ± 1.7 g · m^{-3}, and total suspended solids: 115 ± 31 g · m^{-3}.

The removal efficiency on average from the above given period was: BOD_5: 56.3% ± 4.4, COD: 57.4% ± 2.3, ammonium nitrogen: 13.6% ± 2.2, total phosphorus: 29.8% ± 3.0, and total suspended solids: 71.7% ± 5.7.

The pollution removal efficiency values seem not to be very high but the very short hydraulic retention time should be taken into account and in accordance with this condition these values are comparable to results of another study [Spychała and Łucyk 2015].

A limiting of initial wastewater surface level by overflow but relatively changeable final wastewater surface level was observed (comparison of results of two following series – Fig. 2).

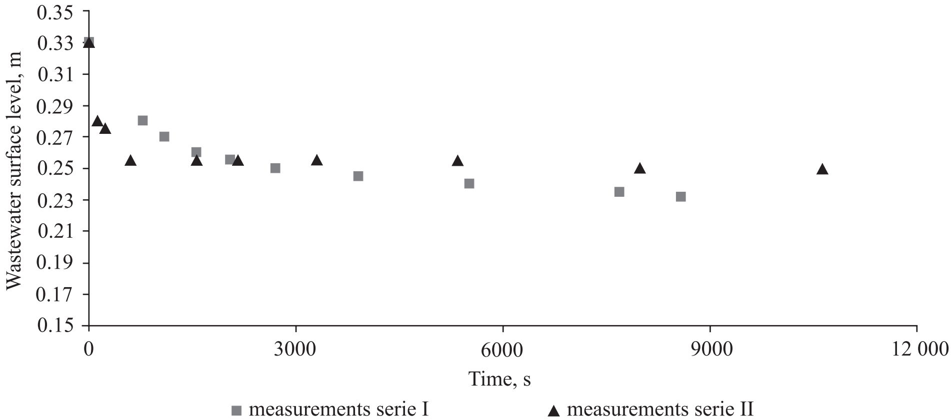

Fig. 2. Wastewater level surface – highly changeable flow-conditions experiment

Slightly changeable flow-conditions experiment

The slightly changeable flow-conditions experiment (at very low changes in wastewater surface level) was carried out on a single filter reactor (four layers of non-woven TS 20 geo-textile of 0.9 mm thickness) during the next several months (07.2014–04.2015) at a limiting of initial wastewater surface level by overflowing pipe and consequently raising the final wastewater surface level due to the filter cake development and reaching the final wastewater surface level about 2.0 cm – 6.0 cm lower than the initial level. The organic loading rate was 0.04–0.07 mg BOD_5/(mg DM · d).

The filter region between initial and final wastewater surface level was covered by fully developed biomass and filter cake as a result of capillary suction of wastewater inside the filtering textile. The filter cake reached during this research period the comparable value for the entire filter height (Fig. 3). These experiment conditions can be considered as slightly changeable in relation to hydraulic conductivity and hydraulic capacity of the entire filter height.

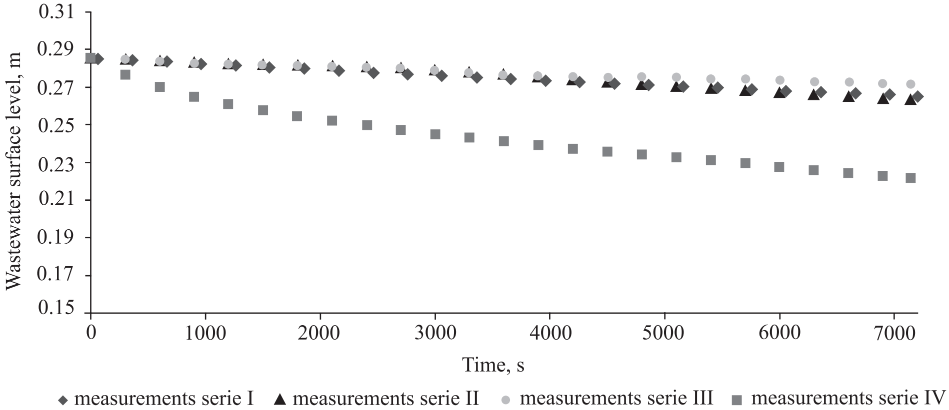

Fig. 3. Wastewater level surface – slightly changeable flow-conditions experiment

Hydraulic conductivity determination

Hydraulic conductivity of filter material coupons was determined using transparent cylinders (1.8 cm, 2.5 cm and 0.75 cm of internal diameter for highly changeable and slightly changeable flow-conditions experiment, respectively, and 32.0 cm and 40.0 cm of length, for highly changeable and slightly changeable flow-conditions experiment) by falling water surface level method after Li et al. [2005].

Coupons of textile were cut out from a filter region continuously saturated with wastewater at heights: 7.5–16.0 cm and 3.0–9.0 cm for highly changeable and slightly changeable flow-conditions experiment, respectively. From a filter region intermittently saturated with wastewater (during highly changeable flow-conditions experiment) coupons were taken at a height between 17.0 and 24.0 cm and between 25.0 cm and 29.0 cm.

Hydraulic model elaboration

The elaborated modelling approach corresponds to the study carried out by Weggel et al. [2011] and Weggel and Dorth [2012].

Due to the variable hydrostatic pressure at different altitudes of the filter, all the layers were divided into ten horizontal zones. The model equations describe the relationship between the volume of the reactor, the area of filtration, the hydrostatic pressure difference and flow of wastewater through the filter (determined by the hydraulic conductivity). The mathematical model assumptions and the basic model parameters were shown in figure 4.

Volume balance for the model can be described by the equation (1):

$$A_p \cdot \frac{dH}{dt} = Q_{in} - Q_{out} \tag{1}$$

where:

A_P – surface area of the reactor in the plan, m^2,
H – height of the wastewater surface in the reactor, m,
Q_{in} – inflow rate, $m^3 \cdot s^{-1}$,

Q_{out} – outflow rate, $m^3 \cdot s^{-1}$,
t – time, s.

Outflow from the reactor equipped with the geo-textile filter can be described as the sum of the outflows to the reactor with full mixing. With regard to the distribution of the filter on the horizontal zones, equation (1) takes the form (eq. 2):

$$A_p \cdot \frac{dH}{dt} = Q_{in} - \sum_{i=1}^{n} q_{out\ i} \tag{2}$$

where:
n – number of zones,
$q_{out\ i}$ – flow through the filter surface of the i-th zone, $m^3 \cdot s^{-1}$.

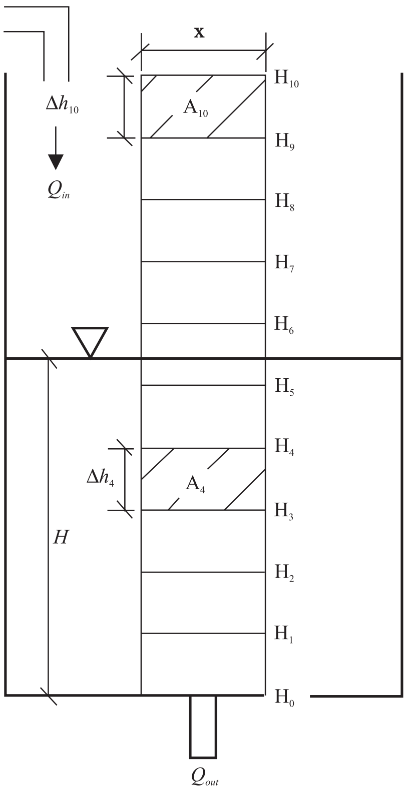

Fig. 4. Hydraulic model assumptions and the basic model parameters

Two different cases of outflow wastewater into the reactor with full mixing can be distinguished:
- the first – the wastewater level is below the zone when $h_i \geq H$, then $q_{out\ i} = 0$,
- the second – the wastewater level is above the zone when $h_i < H$, then the outflow from the zone can be described as follows (equation 3):

$$q_{out\,i} = k_{fi} \cdot \frac{h_i - h_{i-1}}{2L} \cdot A_i \quad (3)$$

where:

- h_i – the height of the zone ($3.3 \cdot 10^{-2}$ for highly changeable flow-conditions test and $2.8 \cdot 10^{-2}$ for highly changeable flow-conditions test), m,
- k_{fi} – hydraulic conductivity of the zone, $m \cdot s^{-1}$,
- L – thickness of the non-woven textile, assumed: $3.6 \cdot 10^{-3}$ m (textile layer thickness) + $4.0 \cdot 10^{-4}$ (filter cake thickness) = $4.0 \cdot 10^{-3}$ m,
- A_i – filter area of the *i*-th zone, m^2.

Hydraulic conductivity of the zone is a hydraulic conductivity of the partly clogged textile filter assuming that biomass grains (particles) are uniformly dispersed in the pore space of the filter, calculated from formula (4) given by Giroud [2005]:

$$k_{fi} = \frac{\lambda \rho_w g}{\eta_w} \frac{\left(n - \dfrac{m}{t_{GT}\rho_s}\right)^3}{\left[\dfrac{4(1-p)}{d_f} + s_v\left(\dfrac{m}{L\rho_s}\right)\right]^2} \quad (4)$$

where:

- λ – shape factor,
- ρ_w – density of water, $kg \cdot m^{-3}$
- g – acceleration due to gravity, $g = 9.81\ m \cdot s^{-2}$
- η_w – viscosity of water, $kg \cdot (m \cdot s)^{-1}$
- p – porosity,
- m – mass of bio-grains reaching the textile filter per unit area of textile, $kg \cdot m^{-2}$
- ρ_s – density of bio-grains, $kg \cdot m^{-3}$
- d_f – fibre diameter, m
- s_v – volumetric specific surface area of bio-grains, assumed $13/d_p$) where d_p is the bio-grains diameter, m

For the modelling simulations the following measurements, calculations and assumptions were made:

- it was posited the simplification that due to the small thickness of the filter cake (0.3––0.5 mm for all filter layer thickness) and due to the lack of evident border between the filter cake and the filter layer, the filter cake is an integral part of the first filter layer (thickness of the filter cake is comparable to the non-woven textile surface roughness (average pore diameter about 0.1 mm, protruding fibers and high differentiation of pores and surface roughness),
- the biomass concentrations in first layer (limiting the flow in the next layers due to the higher biomass concentration comparing to the next layers) were as follow: 11.9 $mg \cdot cm^{-2}$ at filter height of 5.0 cm, 11.1 $mg \cdot cm^{-2}$ at filter height of 10.0 cm and 8.5 $mg \cdot cm^{-2}$ at filter height of 20.0 cm,

- the average particles diameter was identified using image analysis of microscopic picture of biomass taken from first textile layer; the observed biomass grains diameter was 1.66 ± 0.01 µm on average (*n* = 30 664); the modelling simulations were performed for average value obtained for other less representative samples image analysis: 2.20 µm ± 0.025 µm (*n* = 20 548) and 1.37 µm ± 0.01µm (*n* = 25 375) particles diameter on average,
- Gregory and Zabel [1990] reported the bioflocs shape factor ranging from 1 up to and even greater than 20 for spherical particles and non-spherical bioflocs, respectively, similar range: 6–18 (6 for spherical particles and 18 for non-spherical irregular particles), was mentioned by Kovács [1981]; Rössle [2008] reported shape factor equal to 20 for an irregular shaped bioflocs; therefore the shape factor for biomass grains was assumed as 13 – an average value for range from 6 to 20,
- the measured effective porosity (reduced by biomass volume) was 0.61 ± 0.03, as the porosity was determined for microscopic specimen fixed at very low hydrostatic pressure, the porosity should be recalculated in terms of pressure conditions in working filter by a correction factor derived from research carried out by Kopitar et al. [2013], equal to 8%, taking this into consideration the porosity value for hydraulic conductivity calculation should be 0.53, the porosity value obtained from the image analysis and assumed for the simulation was comparable to value reported by Hong et al. [2007] – between 0.68 and 0.85; similar vale of clogged filtering textile (61%) was also reported by Spychała et al. [2013] for other geo-textile type; the filter layer thickness decrease was similar at whole filter height due to the tension acting at the entire filter layer surface,
- no statistical difference was observed in porosity of filter zones (at different filter height) due to: the high changeability related to biomass concentration, textile fibres local density and porosity, changeable conditions (biomass growth limited by drastic changes in wetting by wastewater and drying due to the wastewater surface level falling), therefore for the mathematical simulation as an another scenario – the porosity adversely proportional to the mass concentration (0.53, 0.57 and 0.74) for zones 1–4, zones 5–7 and zones 8–10, respectively was analysed.

The algorithm below was used for the calculation of flow through a non-woven filter.
First time step:

1. Calculation of the volume of wastewater flowing into the reactor in a given time step (eq. 5):

$$V_{in} = \frac{Q_{in}}{\Delta t} \tag{5}$$

2. Calculation of the initial wastewater height in the reactor in a given time step (eq. 6):

$$H_t = \frac{V_{in}}{A_p} \tag{6}$$

3. Calculation of the initial and final wastewater height of consecutive zones (values of $h_1, \ldots, h_{10}$).
4. Summarizing of all $\sum q_{out\ i} = Q_{out}$ values after first time step.

Second time step:
1. Calculation of the new value of wastewater surface level using equation 7:

$$H_{t+\Delta t} = H_t + \frac{Q_{in} - \sum q_{out\ i-t}}{Ap} \Delta t \tag{7}$$

where:
$H_{t+\Delta t}$ – height of the wastewater surface in the reactor at the time step, m,
H_t – height of the wastewater surface in the reactor at the previous time step, m,
$\Sigma q_{outi\text{-}t}$ – flow through the filter surface of the *i*-th zone at the time step, $m^3 \cdot s^{-1}$.

2. Calculation for zones: $h_1 \rightarrow h_{10}$ in time $t + \Delta t$.

Next time steps performance – the same procedure like during the first time step.

Using equations 1–10 the hydraulic model was implemented in the Matlab–Simulink software.

RESULTS AND DISCUSSION

Hydraulic capacity of filters observed during this study (10^{-4}–10^{-5} cm · s^{-1}) was comparable to the value reported by Peter-Varbanets et al. [2011] for filter cake formed on the surface of the membrane during gravity-driven, dead-end ultra-low pressure ultra-filtration 1.0 $dm^3 \cdot (h \cdot m^2)^{-1}$ – about $2.8 \cdot 10^{-5}$ cm · s^{-1}. The results showed that hydraulic conductivity and filters capacity was related to the wastewater surface level conditions (highly changeable and slightly changeable) and horizontal zones of the filter height hydraulic conductivity (tab. 1).

The hydraulic conductivity of filtering material coupons taken from regions continuously saturated with wastewater (7.5–16.0 cm form reactor bottom) was $5.7 \cdot 10^{-9}$ cm · s^{-1}. A higher hydraulic conductivity was observed for coupons taken from regions intermittently saturated with wastewater: 17.0–24.0 and 25.0–29.0 cm form reactor bottoms – $4.6 \cdot 10^{-5}$ cm · s^{-1} and $6.8 \cdot 10^{-5}$ cm · s^{-1}, respectively. These differentiated hydraulic conductivity values were related to the biomass concentrations in different zones of filter height: 11.9 mg · cm^{-2} at filter height of 5.0 cm, 11.1 mg · cm^{-2} at filter height of 10.0 cm and 8.5 mg · cm^{-2} at filter height of 20.0 cm.

During the highly changeable flow-conditions experiment the wastewater surface level reached the initial value at the start of dosing but at the end of the dose (just before another dose) the wastewater surface level was relatively low. Due to the short time of contact of the region intermittently saturated with wastewater and limited conditions for biomass growth, the hydraulic conductivity was higher. The hydraulic conductivity of the region continuously saturated with wastewater due to its permanent contact with the latter and better conditions for suspended solids accumulation and biomass growth was the lowest.

The instability of conditions was confirmed by different wastewater surface level values and outflow measurement carried out in a short time – four days (between the two following series results: 9th August and 13th August). In this period the initial wastewater surface level varied from 19.5 cm to 22 cm and the final wastewater surface level at the end of measurement varied from 5 cm to 10 cm.

Table 1. Detailed empirical results

Specification	Highly changeable flow-conditions experiment		Slightly changeable flow-conditions experiment	
	Experiment – reactor	Hydraulic conductivity determination	Experiment – reactor	Hydraulic conductivity determination
Filtering surface (at initial wastewater surface level), cm^2	320	4.9	601	1.8
Ap, cm^2	42.7	–	95	–
Filter layer thickness, cm	0.4	0.4	0.4	0.4
Initial wastewater surface level, cm	19.5–22.0	25.0	28.5	40.0
Final wastewater surface level at the end of measurement, cm	5.0–10.0	24.9	22.2–27.1	36.5
Hydraulic conductivity of zones 1–4, $cm \cdot s^{-1}$	–	$5.7 \cdot 10^{-9} \pm 3 \cdot 10^{-10}$	–	$3.5 \cdot 10^{-7} \pm 4 \cdot 10^{-8}$
Hydraulic conductivity of zones 5–7, $cm \cdot s^{-1}$		$4.6 \cdot 10^{-5} \pm 7 \cdot 10^{-6}$		
Hydraulic conductivity of zones 8–10, $cm \cdot s^{-1}$		$6.8 \cdot 10^{-5} \pm 5 \cdot 10^{-6}$		

The highly changeable conditions in the intermittently saturated region were related to relatively long periods between doses, starvation of biomass, drying of biomass and the local density, and pore size of textile. The observed hydraulic conductivity of regions of filter intermittently saturated with wastewater tended to decrease with time as a result of biomass growth.

Due to the intermittent dosing and long periods with low wastewater surface level during highly changeable flow-conditions experiment the biomass of filter was sensitive to drying. Several measurement series showed that even a several-hour period between doses caused an increase in hydraulic capacity due to the drying of biomass (extra-cellular polymeric substances could play a decisive role in structural changes, volume of particles reduction due to water loss and live organisms starvation). These measurements showed that the filter biomass, especially in the top region of filter is very sensitive to inflow qualitative and quantitative characteristics. The high impact of time duration between doses and biomass, and hydraulic capacity sensitivity was noted earlier [Głaz 2013]. The time-changeable biomass concentration resulted in hydraulic conductivity and wastewater level changes. Therefore the precise hydraulic conductivity identification at a different filter height was practically impossible. The filter biomass changeability (related to the e.g. hydraulic conductivity) at higher filter altitude was related (probably) to the e.g. wastewater spreading resulting from the dose inflow. The lower the biomass concentration, the lower the resistance to drying.

During the slightly changeable flow-conditions experiment the differences in permeability and hydraulic conductivity of different filter height zones (regions) were much smaller. So it might be argued that the hydraulic conductivity value was more or less similar for whole height of the filter based on measurements.

For the mathematical simulation at highly changeable-conditions flow (highly changeable wastewater surface level) the porosity adversely proportional to the mass concentration (0.53, 0.57, 0.74) was analysed (for 1.66 μm average bio-granule diameter) and values related to the calculated porosity were: $4.1 \cdot 10^{-6}$ cm · s^{-1}, $6.5 \cdot 10^{-6}$ cm · s^{-1} and $3.5 \cdot 10^{-5}$ cm · s^{-1} for zones 1–4, zones 5–7 and zones 8–10, respectively. The hydraulic conductivity at slightly changeable-conditions flow (low changeability of wastewater surface level) was calculated (for 1.66 μm average bio-grains diameter) for averaged porosity (0.53) and was $9.4 \cdot 10^{-7}$ cm · s^{-1} (Tab. 2, Fig. 5, Fig. 6).

The verification of highly changeable flow-conditions mathematical model by the experiment data set proved to be satisfactory, however the model results were sensitive to average bio-grains diameter and effective porosity.

The hydraulic conductivity values calculated from the Giroud [2005] formula (Table 2) were different from values observed during hydraulic determination test (Table 1).

Plotted modelling wastewater levels in the reactor (assuming for modelling the real dimensions of the reactor: filtering surface and plain view surface area of effective wastewater table in the reactor) were shown in figures 5 and 6. The final values (after two hours of filtration after dose application) were similar to observed during experiment (Table 1).

The agreement of modelled values with measurement values was satisfactory.

The modelling simulations showed that the Giroud [2005] approach is a useful tool for TFWT permeability modelling, especially when it is a need to modelling the flow through the filters working at changeable wastewater level. The Giroud [2005] formula can be used for bio-grains in textile clogging although it was evolved for soil particles clogging. The calculated and experimentally identified hydraulic conductivity values were comparable (taking into consideration the order of magnitude) to the hydraulic conductivity value reported by Giroud [2005] for textile clogged with clay (characterized by porosity of 0.4 and particle diameter of 1.0 μm).

McIsaac and Rowe [2006] observed hydraulic conductivity of clogged non-woven geo-textile (two types of combination: GTF/S and GTMF) between $2 \cdot 10^{-5}$ m · s^{-1} and $1 \cdot 10^{-4}$ m · s^{-1}. The hydraulic conductivity of clean geo-textiles was measured between $4 \cdot 10^{-4}$ m · s^{-1} and $5 \cdot 10^{-4}$ m · s^{-1} respectively. The difference shown between clean and clogged geo-textiles in the McIsaac and Rowe research [2006] was about one order of magnitude only. The observed hydraulic conductivity of clogged non-woven geo-textiles by McIsaac and Rowe was much higher than identified in this study. The difference was related to the nature of the clogging material (landfill leachate in the McIsaac and Rowe study).

A significantly different decrease in the flow rate of geo-textiles (two geo-textile types combination and single layer) due to the accumulation of fly ash and dredged sediments in form of filter cake was observed by Kutay and Aydilek [2004] – about two-three orders of magnitude.

A comparable to observed in this study values were obtained by Thanh and Dan [2013]: between $4.4 \cdot 10^{-5}$ cm · s^{-1} and $1.7 \cdot 10^{-4}$ cm · s^{-1} ($8.6 \cdot 10^{-5}$ cm · s^{-1} on average).

Table 2. Detailed modelling results

Zones	Average bio-granule diameter											
	1.66 µm				2.20 µm				1.37 µm			
	Highly changeable flow conditions		Slightly changeable flow conditions		Highly changeable flow conditions		Slightly changeable flow conditions		Highly changeable flow conditions		Slightly changeable flow conditions	
–	*p*	*k*, cm · s^{-1}	*p*	*k*, cm · s^{-1}	*p*	*k*, cm · s^{-1}	*p*	*k*, cm · s^{-1}	*p*	*k*, cm · s^{-1}	*p*	*k*, cm · s^{-1}
1–4	0.53	$4.1 \cdot 10^{-6}$	0.53	$9.4 \cdot 10^{-7}$	0.53	$6.9 \cdot 10^{-6}$	0.53	$1.6 \cdot 10^{-6}$	0.53	$2.8 \cdot 10^{-6}$	0.53	$6.5 \cdot 10^{-7}$
5–7	0.57	$6.5 \cdot 10^{-6}$	0.53	$9.4 \cdot 10^{-7}$	0.57	$1.1 \cdot 10^{-5}$	0.53	$1.6 \cdot 10^{-6}$	0.57	$4.6 \cdot 10^{-6}$	0.53	$6.5 \cdot 10^{-7}$
8–10	0.74	$3.5 \cdot 10^{-5}$	0.53	$9.4 \cdot 10^{-7}$	0.74	$5.9 \cdot 10^{-5}$	0.53	$1.6 \cdot 10^{-6}$	0.74	$2.4 \cdot 10^{-5}$	0.53	$6.5 \cdot 10^{-7}$

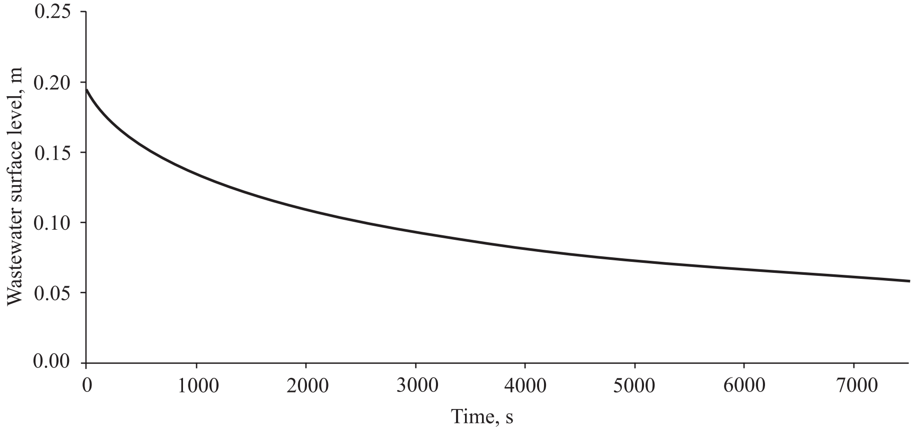

Fig. 5. Verification of highly changeable flow-conditions mathematical model by the experiment data set (porosity: 0.53, 0.57, 0.74 for zones 1–4, 5–7 and 8–10, respectively and bio-grains diameter: 1.66 ± 0.01 μm).

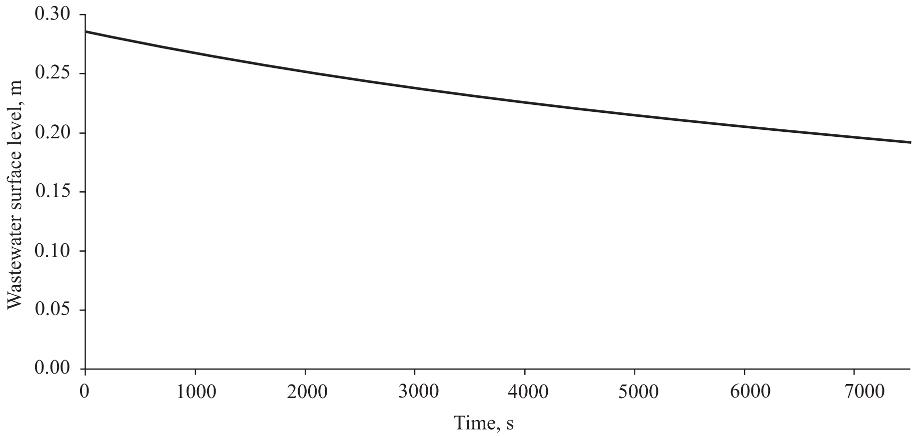

Fig. 6. Verification of slightly changeable flow-conditions mathematical model by the experiment data set (porosity: 0.53 and bio-grains diameter: 1.66 ± 0.01 μm).

The model allows predicting the hydraulic capacity of filter after a specified time period knowing the hydraulic conductivity of regions related to filter height and flow--conditions (e.g. intermittently or continuously saturated with wastewater).

Using the analyzed model the prediction of hydraulic capacity and wastewater surface level for relatively high filters of up to 1.0 m of height is possible. Filters of this height were investigated during textile filters for a wastewater treatment study [Spychała et al. 2013] however the initial wastewater level was not verified as it was not the aim of the study and the experiment duration was too short to develop a biomass concentration (and flow resistance) enabling wastewater surface level higher than about 30 cm.

It was shown that filtration conditions were changeable and related to many factors. TSS concentration was differentiated in time, which could have an impact on the filter cake and textile layer permeability. The measured hydraulic capacity values were differentiated in time and the dry mass concentration measurements showed high differences. The filtering media was sensitive to many factors, which resulted in the changeability of hydraulic capacity in time and final wastewater surface level. In this context, changeable conditions were found in relation to surface area (local differentiation in filter permeability and filtration conditions), as well as time and height of the filter (changeability of filter cake facilities).The other possible reasons for filtration condition changeability could be due to *Protoza* and *Psychoda sp.* fly activity [Spychała et al. 2015].

The model is useful for the simulation of this filter type operation at changeable initial wastewater surface level but relatively detailed information related to hydraulic conductivity is preferable and helpful.

CONCLUSIONS

Based on the research the following conclusions are drawn:

- from the practical point of view a prediction of dose cumulated outflow using hydraulic model is useful, even when the hydraulic capacity and conductivity during particular phases of dose filtration is modelled less accurately,
- the proposed modelling approach in spite of its simplicity provides a satisfactory agreement with empirical data and enables to simulate the hydraulic capacity of vertically oriented filters at changeable wastewater surface level for many zones of filter height that exhibit differentiated hydraulic conductivity values,
- the proposed mathematical simulation enables to predict some TFWT operational features, e.g. the volume of wastewater permeated during a certain time period, average hydraulic capacity of filters (knowing some model parameters values) and the initial and final wastewater level in the reactors, thanks to which the appropriate dosing could be anticipated and modified in appropriate time,
- the formula reported by Giroud [2005] is a useful tool for hydraulic conductivity assessment in textile filters, however is sensitive to porosity and bio-grains diameter and shape,
- the mathematical model reflects the significant impact of operational conditions (duration of periods between doses, initial and final wastewater surface level) on the flow conditions,
- due to the high changeability in time and space (surface) of textile filter biomass and their impact on filter permeability a better modelling result can be obtained for a long period (average of several weeks experimental value) than for single cycles of dosing,
- a more complete utilization of this model with more detailed and precise hydraulic conductivity related data is highly desirable; the collection of this information requires further studies in the relevant field; further research should include:
  - the impact of cake - the thickness, weight, porosity (subsidiary of hydrostatic pressure), composition - in particular the involvement of particles other than oval, with particular emphasis on fiber particles,
  - a detailed analysis of effective porosity (including biomass) dependents on the compression of the nonwoven textile.

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WYDATEK FILTRÓW WŁÓKNINOWYCH DO OCZYSZCZANIA ŚCIEKÓW PRZY ICH ZMIENNYM POZIOMIE – MODEL HYDRAULICZNY

Streszczenie. Celem badań był matematyczny opis wydatku hydraulicznego filtrów do oczyszczania ścieków przy ich zmiennych poziomach pomiędzy kolejnymi dawkami z uwzględnieniem czynników decydujących o przepływie w warunkach filtracyjnych. Przeprowadzono testy w warunkach silnie i słabo zmiennego poziomu ścieków (przepływu) na reaktorach wyposażonych w filtry włókninowe. Określono przewodność hydrauliczną skrawków materiału filtracyjnego. Oznaczono suchą masę pokrywającą powierzchnię filtrów i znajdującą się wewnątrz materiału filtrującego. Opracowany został model matematyczny. Wydatki obserwowane w ramach testu z silnie zmiennym poziomem ścieków były znacząco zależne od zróżnicowanych wartości przewodności hydraulicznej poziomych stref warstwy filtracyjnej. Podczas eksperymentu ze słabo zmiennym poziomem ścieków różnice w przepuszczalności i przewodności hydraulicznej poziomych stref warstwy filtracyjnej były znacznie mniejsze niż podczas testu z silnie zmiennym poziomem ścieków.

Proponowane podejście do modelowania pomimo swojej prostoty zapewnia zadowalającą zbieżność z pomiarami doświadczalnymi, a zatem umożliwia symulację wydatku filtrów włókninowych usytuowanych pionowo. Model matematyczny odzwierciedla znaczący wpływ uwarunkowań filtracyjnych (przepuszczalność włókniny na różnych wysokościach filtra) oraz warunków operacyjnych (częstotliwość dawkowania) na wydatek filtrów włókninowych.

Słowa kluczowe: wydatek hydrauliczny, współczynnik filtracji, odpływ z osadnika gnilnego, filtry włókninowe do oczyszczania ścieków

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