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Should variable declining rate filters be operated as one large or several separate plants?

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ABSTRACT

One of the most practical theoretical models of variable declining rate filters elaborated by Di Bernardo leads to the conclusion that flow rates through filters can be approximated by elements of geometrical progression. This progression has a common ratio lower than 1, so the total sum of its infinite elements is limited. A discussion of the consequences resulting from that conclusion to large filter plants consisting of many units is presented. The first clearly visible limitation of filtrate production from plants consisting of many units operating under the heights of water fluctuation that were the same as used for the operation of small filter plants was illustrated. However, it was then proven that even for many unit filter plants, controlled in such a way as to keep the required ratio of the largest to the average hydraulic loads in the plant, the resistance to the flow of the most clogged filter media is practically independent on the total number of filters. It means that properly operated large filter plants are not subject to production limitations because of the large number of filtration units.

Keywords: Variable declining rate filters; VDR; Large filter plants; Mathematical modeling of filtration

1. Introduction

Variable declining rate (VDR) control systems are mostly used for economical purposes. It has been proven for small filtration units that longer filtration runs, or higher total plant capacity can be reached due to the replacement of constant rate filtration control devices by orifices installed at the outflows from the rapid filters [1–6]. Despite several attempts to model VDR filters operated in a bank, the most practical is the one developed originally by Di Bernardo [7,8] and then simplified by reducing the number of equations and unknowns [9]. In this method, only the simple rules of fluid mechanics are applied and no assumptions on the doubtful kinetics of filter media clogging are made. The Di Bernardo model is described in detail elsewhere [7–11] and some other models of VDR filter plants in the papers [12–15]. This results in reliable calculations but in return does not deliver any information on the filtration run length. The design calculations give results very close to the experimental measurements [16,17], for pilot plants and small filter plants on a technical scale. However, there is no evidence that this method of computation is also highly accurate for designing filter plants consisting of many filters.

In the experiments [16,17], a theoretical assumption was confirmed that the longest filtration runs refer to the highest resistance of the most clogged filter, just before its backwash. The impact of the number of filters in a plant on this resistance is discussed here. A simplified solution to the set of equations describing VDR filter plant performance approximates the flow rates through filtration units by elements of a geometrical progression. The common ratio of this geometrical progression is lower than one, so the total outflow from a plant including an infinite number of units is bounded [9].

This statement suggests that the combining of VDR filters in large banks may be economically unfeasible. However, there are no filter plants consisting of an infinite number of filters. The purpose of the present study is to examine the impact of the number of filters in a bank on the economy of a VDR control system.

2. Set of equations

In general, the following requirements are made in respect of VDR filter plants [18,19]:

- the inflows to the filter boxes are located below the lowest water level above the filter media,
- the orifices are installed at the outflows from the filters,
- the head losses in the pipes are so small, that they can be neglected in comparison with the head loss of flow through the filter media.
- the plant should consist of at least four filters.

The first three requirements are necessary for considering the variable in time water level to be the same at any point of time above all the filter media. The final requirement ensures that the changes of flow through the filters remaining in service are slow enough during the backwashing of the most clogged filter media so they do not impact visibly filtrate quality.

Rapid filters operated in the VDR system are equipped with identical orifices, usually installed at the outflows from each of the units. The installation is done in such a way as to avoid the flow of water for backwash purposes through the orifices. The filters are backwashed in different points of time, so the media of filters backwashed more recently have higher permeability and produce more waters. Between subsequent backwashes in a plant, the water level rises from the lowest level P_1 to the highest level before the next backwash P_2. During this period of time, the flow rates through each of the filters are different but almost constant in time [16–19] because the accumulation of water above all the filters is negligible so that any decrease in flow rate through one of the filters would result in an increase of flow rate through the remaining units. After each of the backwashes, the flow rates through all the filters change dramatically. The pattern of flow rates and the level of water changes in time are presented in Figs. 1 and 2 as results of measurements performed on a VDR pilot plant consisting of four units and constructed at the Cracow University of Technology (Poland) [16,17]. The flow q_1 through the freshly backwashed filter becomes the largest, and the flow q_z through the most clogged filter z the smallest – see Fig. 2. Because of this sudden change, the system of filters' plant operation is called a VDR.

Di Bernardo [8] considered the head loss of flow through a filter plant just after and before a subsequent backwash. He simplified the mass balance equation (3) by neglecting the variations of water storage above the filter media. The performance of a VDR filter plant consisting of z filtration units is described by the set of Eqs. (1)–(3) [9]:

$$H - h_0 = c_1 \times q_1 + c_2 \times q_1^n \tag{1}$$

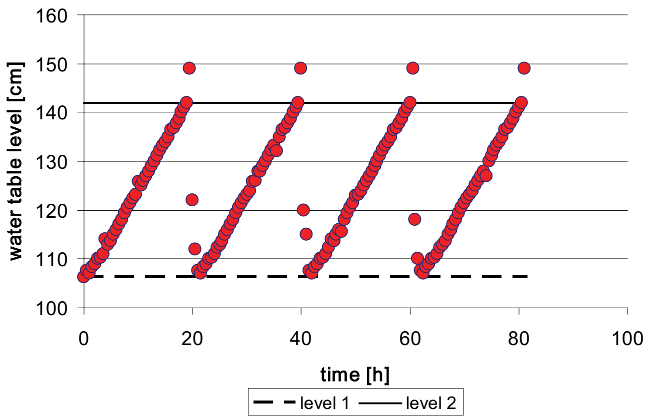

Fig. 1. Surface water table fluctuations pattern above all VDR filters measured at a laboratory set up constructed at the Cracow University of Technology (Poland).

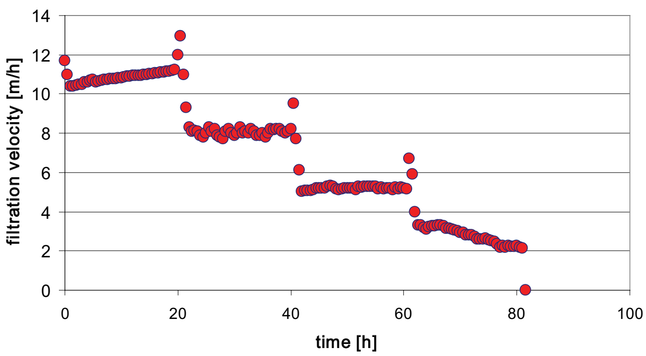

Fig. 2. Simplified flow rates fluctuations pattern for measurements as reported in Fig. 1.

$$\frac{H - h_0 - c_2 \times q_{i+1}^n}{q_{i+1}} = \frac{H - c_2 \times q_1^n}{q_i} \tag{2}$$

$$Q = \sum_{i=1}^{i=Z} q_i \tag{3}$$

The following notations are introduced: c_1 – proportional coefficient characterizing the resistance of the clean filter medium, c_2 – coefficient of turbulent head losses, H – total head loss available in the system equal to the rise of the water level P_2 over the weir in a clean water well, if the head loss in the effluent pipes is insignificant, h_0 – the height of the water table increase between the levels P_1 (just after backwashing one of the filters in the bank) and P_2 (just before backwashing one of the filters in the bank), n – exponential coefficient of nonlinear head loss of flow-through drainage and orifice, q_i – flow rates through i – unit, $q_i = q_1$ for $i = 1$ etc., Q – the total flow rate through the system, z – the number of filters in a plant.

Eq. (1) describes the head loss of flow through a filter just after its backwash, the second set of (z–1) Eqs. (2) compare the ratio of laminar linear head losses through the filter media to the flow rate through each of the filters, just before and after a subsequent backwash in a plant. Eq. (3) is an approximated mass balance according to which the total inflow to the plant is equal to the outflow.

3. Methods

A simple realistic model of VDR Filter plants developed originally by Di Bernardo [8] and then simplified [9] was used for calculating the most clogged filter resistance to flow just before its backwashing. Our previous experiments carried out on a laboratory/pilot scale VDR operated plant confirmed the excellent accuracy of this model [16,17]. The model was also verified [20] with a unit bed element (UBE) model and Arboleda theoretical model [6]. Measurements from small filter plants of technical scale confirmed the excellent accuracy of this model [21]. According to my previous considerations [9] based on approximation of flow rates through filters by elements of a geometrical progression, I suggested that the production of large filter plants may be the subject of limitation because of unacceptable high resistance to flow by the most clogged filter media. Now, using the approximation of flow rates through the elements of geometrical progression, it is discussed when this limitation is visible and when not. Then the rigorous mathematical solution of the full set of equations describing the Di Bernardo model was applied for verification purposes of the conclusions.

3.1. Simplified model

A numerical method of solving the system of Eqs. (1)–(3) developed by Dąbrowski [9] is based on a set of inequalities that binds the solution in the form of $q_1 \ldots q_i \ldots q_z$ from the upper sides $q_{1+} \ldots q_{i+} \ldots q_{z+}$ and from the lower sides $q_{1-} \ldots q_{i-} \ldots q_{z-}$, where $q_{1-} < q_i < q_{i+}$. The number of filters in a bank is denoted by z. The upper bounds are used to calculate the more precise lower bounds and vice versa, so in practice, any required accuracy of the computations can be achieved. The computations start from the less precise approximation of flow rates through filters q_i by elements of a geometrical progression:

$$q_i = q_1 \left(\frac{1 - h_0}{H} \right)^{i-1} \tag{4}$$

In spite of the fact that this approximation is used exclusively for starting the iteration process, and it is inaccurate, some properties deduced from it are confirmed by a rigorous solution to the set of Eqs. (1)–(3) and supported by experimental evidence [17] for a small number of filters.

For example, if someone wants to operate a plant for various H values with the same flow rates through all of the filters, according to the approximated Eq. (4) it is enough to:

- change the height of water fluctuation above filters h_0 proportionally to H, so the ratio of h_0/H is constant,
- change the orifice opening in such a way as to calculate the same value of q_1 from Eq. (1), for new (c_2).

To verify this rule for a plant consisting of many filters, an example of the computations is presented here for the following data. There are z = 20 filters in a plant, total head loss before subsequent backwashing in the plant equals first H = 1.4 m, then H^* = 2.0 m and finally H^{**} = 2.4 m. The coefficient c_1 is calculated for the clean porous media creating 24 cm of head loss for the filtration velocity 3 m/h and for specified water temperature. The computed values of flow rates q_i refer to one square meter of filter media, so the real flow through a filter "i" (where i = 1……20) is the product of q_i and the single filter surface A_{filter}. The VDR system of a filter plant operation requires identical filter units, so the surface A_{filter} and the coefficient c_1 are the same for all the filters i = 1……z. Because the computed flows q_i refer to one square meter of each of the filters "i", they can be expressed as the ratio of flow and filter surface, and they are equal to the hydraulic loads of the filters.

In the computations, the total plant capacity Q is the sum of flows through one square meter of each of the filters, so it is recognized here as the sum of all the filters' hydraulic loads. The exponent n from Eqs. (1) and (2) was assumed to be equal to 2.0, which is the highest possible value. Usually, this coefficient is in a range between 1.6–1.8, and the value n = 2.0 results in the highest possible nonlinearity of the Eqs. (1) and (2) so perhaps creates a lower accuracy of the approximation of the flow rates through the filters q_i by elements of a geometrical progression (4) [9]. The testing of this approximation is one of the tasks of this paper. The computations were done for the ratio q_1/q_{avr} = 1.3, where q_1 is the hydraulic load of the filter just after its backwash and q_{avr} is the average value of the hydraulic load in the filter plant. The ratio 1.3 is usually assumed in the U.S.A. for designing purpose of the VDR control system, and this ratio used to be no higher than 1.5 as a result of the consideration of low filtrate quality risk. However, the impact of filtration velocity on filtrate quality depends on the coagulation and flocculation parameters' rationality, and then on the mechanism controlling the transportation process in porous media. Sudden changes in flow rates and surging degrade filtrate quality [22], while in our own experiments sometimes higher filtration velocities produced filtrate of lower turbidity.

The accurate results of numerical solving the set of Eqs. (1)–(3) for the same plant capacity q_i = 80 m^3/(m^2/h) (the sum of all hydraulic loads for 20 filters) and for H, H^*, H^{**} are presented in Fig. 3. The rigorous numerical solution to the set of Eqs. (1)–(3) confirms the simple rules of adjusting h_0 and c_2 in a way to maintain the same h_0/H ratio, and c_2 in a way to receive all three times the same q_1 values, resulting in almost the same hydraulic loads of the filters. For a laboratory setup consisting of only four filter columns of an inside diameter of about 100 mm each [17], the simple rules of adjusting h_0 and c_2 to keep almost constant q_i values were confirmed experimentally. Similar to this study, the solution to the full set of equations in the Di Bernardo models (1)–(3) confirmed these rules. Moreover, a simple UBE model was also used [20] for testing purposes and all the results gave a similar confirmation. However, now the numerical solutions confirmed the first time round applied the same rule, but for a plant consisting of a large number of filtration units.

In Fig. 3 only flow rates for filters of numbers 1, 5, 10, 15, 20 were drawn for the readability of the chart.

3.2. Optimization considerations

It was theoretically deduced [14] from the Di Bernardo model Eqs (1)–(3) that the most clogged filter media was just

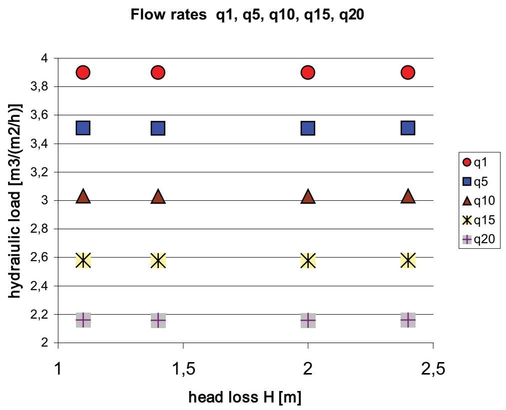

Fig. 3. Applying the rule of adjusting h_0 and c_2 to different H values in the way to ensure more or less constant q_i values. The numerical tests were performed using the set of Eqs. (1)–(3), and the rules resulted from a simplified model in which Eq. (2) was substituted by an approximate relation $q_{i+1} = q_i(1–h_0/H)$ were confirmed.

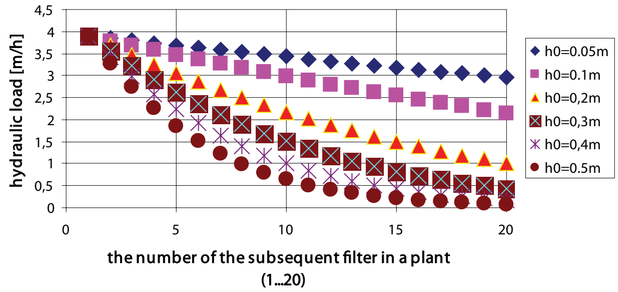

Fig. 4. Hydraulic loads of 20 filters in a bank for h_0 from 0.05 to 0.5 m.

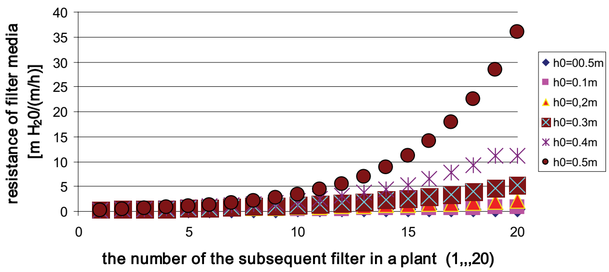

Fig. 5. Resistance of 20 VDR filters' media just before backwashing of the filter "z" for the same data as used for the computing of flow rates as presented in Fig. 3.

before its backwash occurs, when the operation of a VDR filter plant is conducting, simultaneously, the highest possible total head loss of flow H with the highest allowable ratio of q_1/q_{avr}, where q_{avr} is the average flow or the average hydraulic load of all the filters. This was proven the first time for VDR plants operating under the rules described in the previous paragraph [9]. Next, it was deduced that any operation not following both these rules results in lower resistance to the flow of filter media just before its backwash. It is expected that higher resistance to the flow-through filter media refers to longer filtration runs. This is a logical assumption confirmed several times experimentally [16,17], but because of a complex distribution of deposit inside of the filter media, depending on the filtration velocity and physico-chemical properties of the suspended solids, it is impossible to prove this assumption in all possible scenarios.

To date, the impact of the number of filters on this resistance has not been investigated. If the flow rates through VDR filters are approximated by elements of a geometrical progression [9,17] with the common ratio below 1, the total sum of flow rates is bounded even for an infinite number of filters. The purpose of the study is to investigate if this theoretical limit impacts in any way on the total flow-rate from large filter plants consisting of many, but a rationally limited, number of filters. Such an impact is presented in Fig. 4, illustrating the hydraulic loads of 20 filters for the same data as used for computations resulting in almost constant flow rates q_i in Fig. 3 and for several values of h_0, starting from 0.05 to 0.5 m. For high values of h_0, the amount of filtrate delivered by the most clogged filters is unacceptably small and the resistance to the flow of filter media extremely large, as presented in Fig. 5. The resistance c_{1z} of filter media 'z' just before its backwash is calculated from Eq. (5) [9,14,17] because at the end of a filter run total head loss is equal to H and flow rate to q_z.

$$c_{1z} = \frac{\left(H - c_2 q_z^n\right)}{q_z} \tag{5}$$

In spite of the fact that the operating conditions from Figs. 3 and 4 of the most clogged filters show uneconomically low water production and unacceptably high resistance of the filter media to the flow, it is still not proven that for 20 filters in one bank the reasonable VDR control system results in the uneconomical operation of the plant. For the safety of water quality, it is necessary not to exceed a given ratio of q_1/q_{avr}. Historically in the U.S.A., it has been equal to 1.3, in Brazil 1.5, and in Argentina up to 2.0 [6]. None of these requirements is fulfilled for too high values of h_0 resulting in extremely low hydraulic loads for $z > 10$ (see Fig. 3). It is well known [6] that larger VDR filter plants are operated with a much lower height of water table fluctuation above the filters. First, it is necessary to properly adjust h_0, and only after that can the impact of the number of filters on the economy of the plant operation be evaluated.

3.3. Required water table fluctuations

To predict the proper height of the water table fluctuations h_0 above the filter boxes, the approximation of the flow-rates through the filters by elements of geometrical progression $q_{i+1} = q_i(1–h_0/H)$ was again used. The sum of q_i from 'z' first elements of this geometrical progression can be computed from Eq. (6).

$$\sum_{i=1}^{i=z} q_i = H \times q_1 \times \left[\frac{1\left(1 - h_0 / H\right)^2}{h_0}\right] \tag{6}$$

The result of a numerical solution to Eq. (6) in the form $h_0/H = f(z)$ for $q_1/q_{avr} = 1.3$ is presented in Fig. 6. For the coefficients c_1, c_2, n and for the average hydraulic load q_{avr},

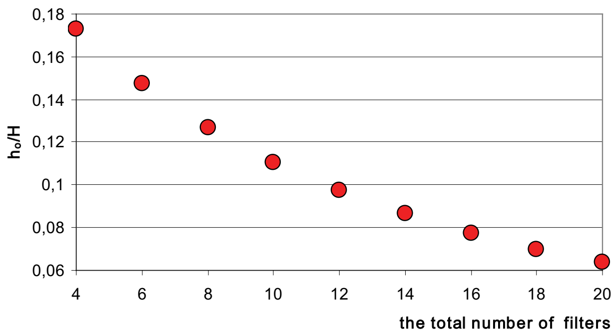

Fig. 6. Ratio of h_0/H required for q_1/q_{avr} = 1.3 as a function of z for the same data as for which the results of previous computations are presented in Figs. 1–5.

the same set of Eqs. (1)–(3) as were used previously for the purpose of constructing Figs. 1–4 and for h_0 predicted from Eq. (6) (Fig. 6) was solved, and the ratio of q_z/q_{avr} calculated for all numbers of filters in a plant starting from z = 4 to z = 20. For all these 16 cases, the received values of q_z/q_{avr} were the same from a technical point of view as they comprised between 0.74 and 0.75.

3.4. Resistance of the most clogged filters

Because all the 16 cases were calculated for the same data including H, c_2, n and practically the same q_z values were received so, according to Eq. (5), the same filter media resistances of flow at the end of filter runs result from the computations. Concluding for the properly chosen ratio of h_0/H, the resistances to the flow of the most clogged filters, just before their backwashes, are the same and a large number of units can be operated economically. The problem is the small fluctuation of the water table in filter plants consisting of many units. For 20 filters, the calculated value of h_0 was six times lower than for four filters. Ultrasound and some other technologies allow for measuring the level of water with an accuracy of a little better than 1 mm, but any disturbance in the flows through the plant can result in the false decision of starting the successive backwash if this decision is based solely on the measurement of the water table level.

3.5. Limitations of the model

The design method of the VDR filter plant developed originally by Di Bernardo [7,8], was used here as a tool for investigating the impact of the number of filters on the average flow through all filters in a bank. In spite of the statements made at the beginning of this text that the reliability of the model by Di Bernardo has been proved many times by comparison both with UBE [17] models and with the results of pilot plants' experiments [16,17] it is important to realize that this practical and generally reliable model is subject to some limitations, like almost all design models used in technical applications. These limitations can be recognized by discussing the assumptions made by Di Bernardo. They can be divided into two groups: independent of the number of filters and characteristic exclusively for filter plants consisting of many units. The first group of limitations refers to fluctuating raw water quality or variable water temperature. If backwashing starts each time for the same value of H–h_0, changes in raw water quality may significantly impact the lengths of filter runs, but the flow rates through all filters remain essentially the same [11]. Unfortunately, changes in water temperature create some deviations from the predicted values of flow rates through VDR filter plants because head loss of flow-through orifices does not depend on water temperature, or head loss of flow-through filter nozzles are impacted by the temperature to some limited value (the flow is of a transition character), but the head loss of laminar – linear flow through filter media depends strongly on the water temperature. In practice, a different mode of operation is required for summer and for winter conditions unless the plant is supplied with groundwater which requires rapid filtration as a part of the iron and/or manganese removal process, and the water temperature is not affected by the season of the year.

For larger plants, it is more difficult to fulfill the requirement that head losses in piping should be negligible in comparison with head losses of flow-through filters. This requirement is necessary for considering the variable in time level of water to be the same at any point of time above all the filters. If this condition is not satisfied, the operation of the plant will be very complex depending on which filter was backwashed most recently. However, for constructing large new filter plants several possibilities exist for reducing friction to flow through pipes or designing water distribution and collection systems in such a way that the head is almost the same at inflows to and outflows from all filter units [14]. For old large plants, this requirement can be very difficult or impossible to fulfill. Additional difficulties in large plants operation can be observed if a channel is used for the distribution of raw water among the filters. In this case, waves are formed in the channel each time a filter is disconnected for backwashing and when it is put back into service again, which creates an additional instability. In conclusion, the changes in flow rates through the filters of large plants are smoother, which may be positive for filtrate quality but makes the operation of the plants more difficult to control.

4. Conclusions

The flow rates through VDR Filters were previously approximated by elements of a geometrical progression [9] with the common ratio lower than 1. The total sum of hydraulic loads q_i even for an unlimited number of filters is bounded so one could expect that, in contrast to small filter plants, the operation of plants consisting of a large number of units is uneconomical. This problem has been tested here. The limitation of the total flow rate is clearly visible if the height of the water fluctuation above the filters is assumed to be of the order of magnitude the same as for a small number of units. However, the resistance of the most clogged filter media is practically independent of the number of filters if the height of water fluctuations above them is calculated in such a way as to keep the same ratio q_1/q_{avr}. The limitation of this ratio is required for ensuring proper filtrate quality. This quality is usually similar to the quality of filtrate produced by Constant Rate Filters of properly operated flow rate controllers [20].

The final conclusion is that, if the height of the water table fluctuation is predicted correctly for a given realistic ratio of q_1/q_{avr}, large VDR filter plants are not subject to production limitation because of too high resistance of the most clogged filter media. However, the problem is that in large plants the height of the water fluctuation above the filter media is very small and can be unstable.

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