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NUMERICAL STUDY OF A RATIONAL RULE FOR THE OPERATION OF VARIABLE DECLINING RATE FILTERS IN RESPONSE TO CHANGES IN RAW WATER QUALITY

A rule for the operation of Variable Declining Rate (VDR) Filter Plants under conditions of sudden changes in influent water turbidity has been tested using a mathematical model based on the Unit Bed Element (UBE) approach. The rule was postulated previously by Dąbrowski and Marzec based on numerical simulation of a filter plant according to the mathematical model of Arboleda et al. Now a UBE model developed by Mackie and Zhao and adapted for Variable Declining Rate operation was used to investigate a plant behaviour in response to rapid changes in raw water quality. Two different cases have been considered. In the first, only the concentration of solid particles was the subject of change, and in the second the particle-size distribution changed as well. Numerical simulations were carried out under various conditions, with backwashing started when the water level above the filters reached the same position. It was found that this resulted in almost identical flow rates through each of the filters, but the length of filter runs and the effluent quality were significantly different. For waters of stable temperature but different turbidities backwashing should start for the same water level above the filters, even if the raw water quality changes.

1. INTRODUCTION

The use of Variable Declining Rate (VDR) Filters has been extended over the last three decades. Their construction is identical to that of Constant Rate (CR) Filters, but they work in a different flow rate control system, which consists of an orifice or partially open butterfly valve. This valve may be located at the inflow, but is usually placed at the outflow from each of the filters in the bank. The orifice and drainage are responsible for turbulent head losses. The operation is controlled by the interaction between the linear laminar head losses in the filter media and the non-linear turbulent head losses caused by orifices and drainage. During a filter run the media become clogged, and this leads to an increase in the head losses across

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the media, but a decrease in the non-linear turbulent head losses caused by the orifice and drainage.

The rationale for the design of VDR Filter Plants is that the turbulent head losses limit the flow through a clean filter, but make a marginal contribution to the hydraulic resistance of clogged filters due to the much smaller flow rates. Laboratory [1], pilot plant [2] and full technical scale [2], [3] observations indicate that the changes in flow rates through the filters occur mostly when one of the filters is disconnected for backwash and just after it is brought back into service. After each subsequent backwash in a plant, the rates of flow through all filters drop except the rate of flow through the now clean filter, which produces water at the highest rate. This is why this system of operation is called Variable Declining Rate. This rule of operation is illustrated in the next paragraphs by the results of computations presented in figures 1 and 2.

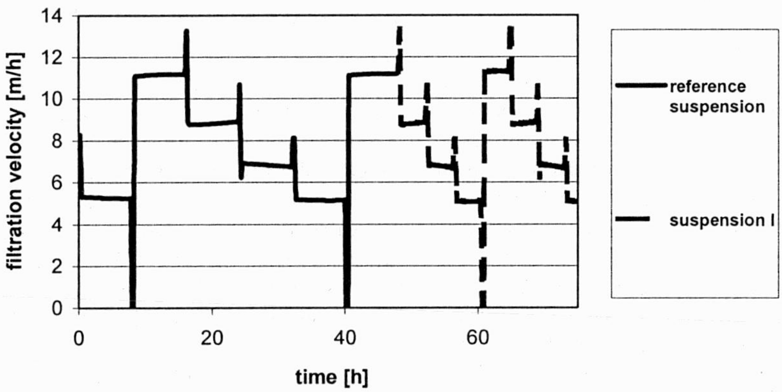

Fig. 1. Flow-rate distribution of four VDR Filters before and after changes in the total concentration of suspension, but for the same relative distribution of size fractions

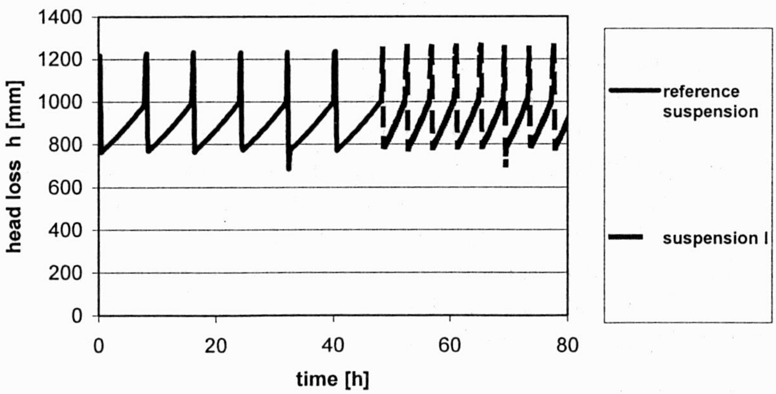

Fig. 2. Illustration of applied rule of the plant management based on the same value of head loss at the moment when next filter is disconnected from the bank for backwash purposes

Several requirements have to be fulfilled to secure effective operation in a Variable Declining Rate Filter Plant. They are as follows:

1. All inflows should be below the lowest water level above filters.
2. Head loss of flow through pipes is negligible compared to the head loss caused by the filters (media and drainage).
3. There must be at least four filters in a plant.

If the first two requirements are fulfilled the water surface is at the same level above all filters at any time of operation. This surface rises gently between backwashes, then rises sharply when the mostly clogged filter is disconnected, to go back down after that filter is brought back into operation. At least four filters are needed in order to ensure that this increase is not too sharp.

When Variable Declining Rate Filters are applied as a part of groundwater treatment system to reduce the concentrations of iron and manganese, both the temperature and raw water quality are stable. However, if the system is chosen to control a filter plant supplied with surface water the situation is radically different and it is necessary to adjust parameters of operation to somewhat fluctuable conditions. The impact of temperature on the parameters of VDR plant operation was discussed by DĄBROWSKI and MACKIE [4]. Now a rule of a plant operation in the case of variable water quality is the subject of concern.

2. PROBLEM DESCRIPTION

Almost all existing models of Variable Declining Rate Filters refer to operation under stable conditions, including raw water turbidity and temperature. However, if a plant is supplied with surface water this assumption is not realistic, so it is important to know how to manage VDR Filters during wet weather when the water of high turbidity is approaching the treatment plant. Using the model of a filter plant by ARBOLEDA et al. [5], MARZEC and DĄBROWSKI [6] suggested that backwashes should start when the same head loss of flow through the filters is reached, regardless of the actual quality of raw water. This rule of operation was expected to produce similar patterns of flow-rate distribution among the filters. However, because of a lack of a comprehensive mathematical model describing kinetics of clogging the filter media it was not possible to properly test this rule.

3. METHOD

MACKIE and ZHAO [7] developed a model of deep bed filtration, which combines two Unit Bed Element models – the Happel for clean and the capillary for clogged filter media, with IWASAKI's [8] phenomenological equations describing simplified mass balance [9] and kinetics of clogging. The model accounts for both non-homogeneity of water suspension and for non-uniformity of media grains. The model has been incorporated into a Variable Declining Rate Filter Plant simulation model, and is now used to test the rule of plant operation in response to variations in the raw water supply turbidity.

In the VDR simulation model the head loss h, in any of the filters in a VDR plant is given by:

$$h = c_{1i} q_i + c_2 q_i^n , \tag{1}$$

where:

c_{1i} – coefficient characterizing the resistance of the filter i; its value is dependent upon the degree of clogging in that filter,

c_2 – coefficient of turbulent head losses,

q_i – flow rate through filter i.

The first term on the right-hand side represents the linear head losses in the filter, and the second term – the turbulent head loss in the drainage and orifice. The head loss is the same for each filter. The UBE (Unit Bed Element) Model is used to represent the filter media and to calculate the removal achieved by the filter, the subsequent clogging of the filter, and the head loss across the filter at any stage. Therefore the effect of the incorporation of the model developed by MACKIE and ZHAO [7] into a VDR plant simulation is to include a much more comprehensive representation of the filter dynamics than has been used in previous models. Furthermore it allows the effects of changes in raw water quality to be modelled in a rigorous manner.

4. NUMERICAL EXPERIMENTS

A Variable Declining Rate Filter Plant consisting of four units was investigated in numerical experiments. The sand filter media were assumed to have a depth of 1 m with the stratification shown in table 1.

Table 1

Filter bed stratification

Filter depth (mm)	Grain diameter (mm)
0	0.467
100	0.480
600	0.704
900	0.768
1000	0.832

The grain size was assumed to vary linearly with each depth shown in table 1. Two particle-size distributions of raw water were considered, referred to as Particle Size Distribution (PSD) I and PSD II. The distributions are shown in table 2.

Table 2

Particle Size Distribution (PSD)

Mean particle diameter (μm)	PSD I (%)	PSD II (%)
0.9	12.7	9.9
1.8	15.5	12.7
3.6	35.2	35.2
7.2	36.6	42.2

During dry weather the filter plant was assumed to be supplied with a suspension of type I of a concentration of 7.1×10^{-6} vol/vol. This is referred to as the reference suspension. The head loss level at which backwashing should be initiated in order to achieve good filter runs is dependent on the total plant capacity required, on the gradation of the filter grains, and on the chosen ratio of q_1 to q_{avr}, where q_1 is the flow through the cleanest filter, and q_{avr} the average flow rate per filter. The value of the ratio used in the current simulation was 1.3, and the head loss level was chosen accordingly.

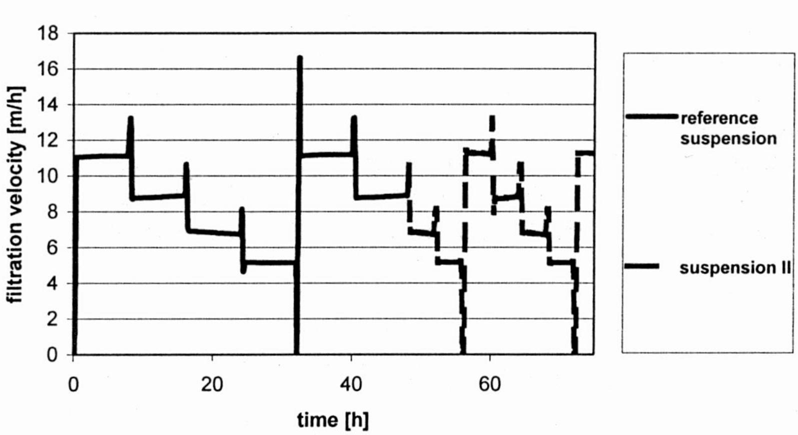

Fig. 3. Flow-rate distribution of four VDR Filters before and after the rise of concentrations of all size fractions of solid particles in raw water

In the first test, the suspension was assumed to still be PSD I, but of double concentration. This is referred to as Suspension I. Subsequent backwashes in the plant started when the total head loss of flow through filter media, drainage and orifice reached the same level as previously. Results of computations are presented in figure 1. In spite of the fact that filter runs shortened significantly (see figure 2), the rates of flow through each filter remained almost undisturbed. A further simulation was carried out where the total concentration was again double that of the reference, but the size distribution was now PSD II. This suspension is called Suspension II and refers to wet weather, so the concentrations of larger particles are higher, while small particles concentrations only slightly increased. In the example considered here, the filters still produce acceptable water turbidity (dependent on computed concentration of suspension) without chemical treatment. It can be seen from figure 3 that again the flow-rate distribution of filters remained almost identical, in spite of visibly shorter filter runs.

5. CONCLUSIONS

Numerical tests carried out on a modern Unit Bed Element Model of Variable Declining Rate Filters Plant developed at the University of Dundee confirmed that the plant should be operated starting subsequent backwashes for the same head loss of flow through a whole single filter unit (including porous media, drainage and orifice, assumed here to be installed at outflows from filters) even if the raw water quality is variable. If this rule of operation illustrated in figures 2 and 4 is followed, then the changes in raw water quality do not significantly affect the flow-rate distribution of filters, and media resistance to flow is at the same level just before a backwash. In this way, a pretty stable operation of a plant is possible in spite of different length of filter runs. This rule of operation was tested in two different circumstances, once changing the total concentration only, and then changing the total concentration and the particle size distribution. In both cases, the system continued to work properly. It is important to remember that the temperature was assumed constant in all numerical experiments in which the method of plant management was tested.

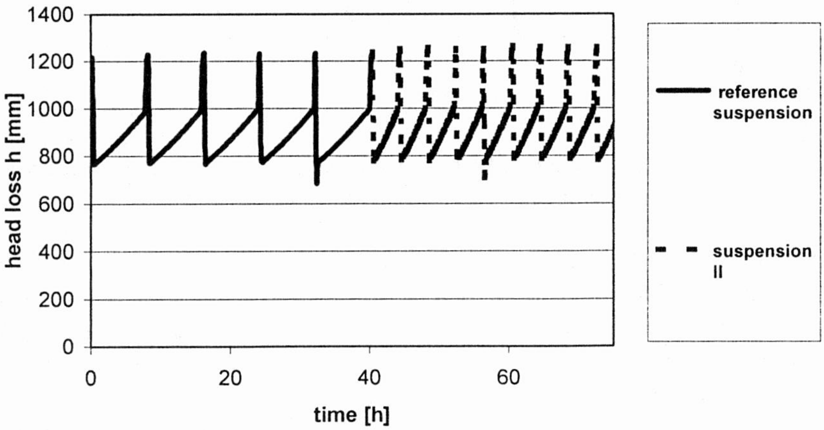

Fig. 4. Presentation of the rule of operation of the plant for Suspension II.
Head losses remain the same at the moment when the most clogged filter is to be backwashed

ACKNOWLEDGEMENTS

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ZASTOSOWANIE MODELU NUMERYCZNEGO DO USTALENIA RACJONALNEGO SPOSOBU STEROWANIA STACJĄ FILTRÓW O SKOKOWO ZMIENNEJ WYDAJNOŚCI W PRZYPADKU ZMIAN MĘTNOŚCI WODY

Zastosowano model fizykochemiczny UBE do symulacji numerycznej stacji filtrów o skokowo zmiennej wydajności, która zaopatrywana jest w wodę surową o nagle zmieniającej się mętności, i przetestowano sposób sterowania pracą takiej stacji. Ten sposób zarządzania pracą stacji zaproponowali wcześniej Marzec i Dąbrowski, korzystając z modelu matematycznego Arboleda i innych. Obecnie fizykochemiczny model filtracji wgłębnej UBE Mackie'go i Zhao, przystosowany do warunków skokowo zmiennej prędkości filtracji przez Mackie'go, został użyty do badania zachowania stacji filtrów w warunkach nagłej zmiany jakości wody surowej. Rozważono dwa różne przypadki. W pierwszym zmieniało się jedynie stężenie cząstek fazy stałej w zawiesinie, a w drugim zmieniały się również frakcje cząstek. Numeryczne eksperymenty wskazały na możliwość utrzymania natężeń przepływu przez każdy z filtrów niemal identycznych jak przed zmianą jakości dopływającej zawiesiny pod warunkiem, że płukanie rozpoczyna się w chwili, gdy zwierciadło wody osiągnie taki sam poziom jak przed tą zmianą. Natomiast długości filtrocykli znacznie odbiegały od obserwowanych podczas pracy filtrów przy uprzedniej jakości wody surowej. Dla zawiesin wodnych o ustalonej temperaturze, ale zmiennym stężeniu, powinno się eksploatację stacji filtrów o skokowo zmiennej wydajności prowadzić tak, aby rozpoczynać kolejne płukania zawsze przy tej samej wysokości zwierciadła wody nad filtrami.