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Influence of Temperature on the Performance of Variable Declining Rate Filters for Drinking Water

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Abstract

A water treatment plant from the Rudawa river was tested in order to investigate temperature influence on the hydraulics of VDR filters. For this filter plant supplied with raw surface water the effect of temperature on head loss in filter media was well documented, but the effect on the turbulent flow through a designed system of orifices proved to be limited. It was found that for the particular plant investigated, peak demands can occur in winter when the water is cold. Concluding, the VDR filters need to be designed for winter conditions but proper operation requires nomograms for the water table fluctuations over the filters as a function of the water demands and temperature.

For the bank of data collected from the tested filter plant the operation based on the same maximum flow through a clean filter led to acceptable fluctuations of the water table. These fluctuations would be much higher if the ratio of the maximum to the average flow-rate in the plant was chosen as a constant parameter of operation instead of the value of the flow rate through a recently backwashed filter.

Notations

A_1 – cross sectional area of a pipe,
A_2 – cross sectional area of an opening,
C – discharge coefficient,
c_1 – coefficient characterizing the resistance of the clean filter,
c_2 – coefficient characterizing the turbulent resistance of an orifice,
d_p – particle diameter,
g_c – conversion factor,
H – head loss in a filter just before backwashing,
h_0 – water level fluctuations between subsequent backwashing,
K – flow coefficient,
K_1 – floc growth coefficient,

K_2 – floc break up coefficient,
Q_a – actual volumetric flow-rate,
Q_i – theoretical flow-rate,
q_1 – flow-rate through a clean filter,
v – approach velocity,
ΔP – pressure difference,
μ – viscosity,
ν – kinematic viscosity,
ρ – density.

1. Introduction

The temperature of water is an important factor in the efficiency of all water treatment processes: coagulation, sedimentation, filtration and disinfection. Not only are treatment processes affected by temperature, but temperature also influences the demand for water and its quality. For example, low water temperatures slightly reduce the removal of organic precursors of trihalomethanes (THM) by coagulation, sedimentation and filtration. On the other hand, surface water is usually of better quality in winter when the reactions that form THM's are slower (Knocke et al. 1986). Finally the total concentration of THM in chlorinated drinking water is usually lower in winter than in summer.

Both the technology and the hydraulics of sedimentation tanks and filters are influenced by temperature. This paper describes the influence of temperature on two aspects of the hydraulics of Variable Declining Rate (VDR) filters. First it is shown how seasonal temperature changes influence the flow-rate through filters, then a method of avoiding deviations of flow-rates from assumed values is presented.

2. Temperature and purification processes

According to Camp and Stein (1943) different temperatures require different amounts of energy to be dissipated in orthokinetic flocculation, but Camp et al (1940) found experimentally that changes in temperature from 1 to 28.3°C had no appreciable effect on the time of iron floc formation in jar tests carried out at optimum pH. Cleasby (1984) argued that the effectiveness of flocculation should be independent of temperature for turbulent eddy flocculation, which is commonly used in water treatment practice. However, he expected that flocculation would be temperature dependent at the very beginning of the process when eddies are smaller than the Kolmogoroff microscale. Hernebring (1981) obtained lower power input levels for maximum settling velocity of iron floc stirred at 18.6–20°C in comparison with flocculation at 1.5–1.9°C. Previously Hedberg (1976) described mathematically the kinetics of flocculation using a so-called floc growth coefficient K_1, and a floc break up coefficient, K_2. When the temperature decreased K_1 decreased and K_2 increased. Cleasby (1984) suggested that floc break up can be temperature dependent even for turbulent eddy flocculation. Miura and Ono (1978) investigated temperature influence on floc formation while studying a computer control model. They obtained lower coagulant doses for higher temperatures and for the same sedimentation velocity. Sedimentation is highly temperature dependent. According to Stoke's law settling velocity is inversely proportional to viscosity. Although Stoke's law is not directly applicable to hindered settling of flocs there is still a strong temperature dependency. The practical importance of this is evidenced by the fact that in topical climates sedimentation tanks are designed for much shorter detention times than in cold climates.

Most transport mechanisms in deep bed filtration are also affected by temperature. Hydrodynamic action depends on the Reynold's number, and molecular diffusion on both the Stokes-Einstein diffusion coefficient and the Peclet number. The effect of gravity is dependent upon viscosity, and thence on temperature. Rajagopalan and Tien (1977) summarized the dependence of the filter coefficient λ associated with diffusion and gravity as follows:

$$\lambda_{diff} \ \alpha d_s^{-5/3} v^{-2/3} d_p^{-2/3} \mu^{-2/3}, \tag{1}$$

$$\lambda_G \ \alpha d_s^{-1} v^{-1} d_p^2 \mu^{-1} \tag{2}$$

where: d_s – collector diameter, d_p – particle diameter, v – approach velocity, μ – viscosity. Surface forces also play a crucial role in deep bed filtration. These forces are particularly important for the filterability of small particles (Rajagopalan and Tien 1979), and they are usually dominated by the London force (attractive) and double layer force (repulsive or attractive). Surface forces and drag forces are both viscosity dependent (Rajagopalan and Tien 1976). Investigating experimentally adhesion of quartz particles and glass beads with diameters of from 30 μm to 35 μm to a smooth quartz plate Sehn and Gimbel (1984) showed both torque due to the shear gradient and drag forces to be proportional to the viscosity of water.

Mackie et al. (1987) assumed that a particle of a given radius cannot be deposited on a grain if a tangential drag force acting on the particle exceeds a critical value. This drag force is proportional to viscosity so lower temperatures would result in smaller critical interstitial velocities, and hence in smaller values of ultimate specific deposit. These expectations agree well with an empirical formula proposed by Hudson (1959) who determined experimentally that the quality of filtrate is acceptable as long as a breakthrough index B (originally called floc strength index, which was proportional to flow-rate and headloss) did not exceed a certain value. The same value of B is reached in shorter runs in winter than in summer. Jackson (1980) stated that often filter performance was better in summer than in winter. For an unflocculated PVC suspension with mean size of 1.3 μm

Ives and Sholji (1965) found an inverse correlation between the filter coefficient λ and the square of water viscosity.

In spite of the difficulties encountered at low temperatures (Jackson 1980) it is possible to operate a filtration plant carefully enough to reduce the turbidity of raw water successfully (Mosher and Hendricks 1986). Al-Ani et al. (1986) even found a strong influence of temperature (which varied between 5 and 18°C) on in line filtration efficiency.

Most of the backwash techniques used in the USA and in Europe require expansion of the filter bed. Minimum fluidization velocity can be determined from the Ergun equation as at the moment of fluidization the headloss is equal to the buoyant weight of the grains (Cleasby and Fan 1981). The first term of the Ergun equation is almost equal to the Kozeny equation and the same head loss is obtained by smaller flow-rates in colder waters. Another approach to minimum fluidization velocity is based on empirical correlations between Galileo and Reynolds numbers, both strongly influenced by temperature (Fan 1978, Dharmarajah and Cleasby 1986, Gunasingham et al. 1979). Practical consequences of the theory are reported in many experimental papers. Camp et al (1971) found that the expansion as a percentage of a filter bed was lower for higher temperatures and for the same wash rate. Kawamura (1975) pointed out that in summer more water is required for backwash purposes. Backwash water demands are particularly temperature dependent for light filter materials such as activated carbon. Nemeth (1978) reported an increase in the required backwash velocity of up to 50% as temperature increased from 5 to 20°C.

3. Variable Declining Rate Filters

Variable declining rate (VDR) filters are self-controlled by orifices creating turbulent head losses in the outflow. These head loses correspond with linear head losses in the filter beds and result in an assumed flow distribution among the filters. The permeability of the media decreases in time because of clogging, and headlosses both in the filter beds and the orifices are functions of time and temperature. This second dependency has not been stressed enough in the literature in spite of the fact that raw surface water temperature varies seasonally in some countries by as much as 25°C. Both kinematic viscosity ν and density ρ depend on the temperature of water, as shown in Figure 1. Though density changes are small, the viscosity does change significantly. It is commonly accepted that the flow through clean and dirty filters obeys Darcy's law (Cleasby and Baumann 1962). This means that at any stage in the filter run the head loss through the filter beds is proportional to the kinematic viscosity, and hence is temperature dependent. However, as most of the transport and attachment mechanisms are also influenced by the temperature the actual effect of temperature on headloss buildup is more complex.

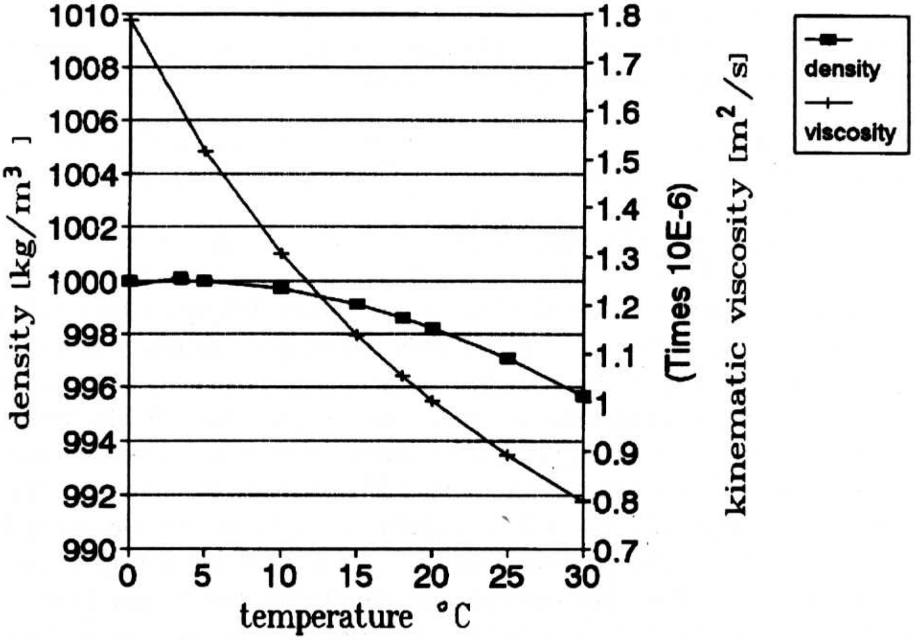

Fig. 1. Variation of density and kinematic viscosity with temperature

Flow through an orifice fulfils the following general role:

$$Q = KA_2\sqrt{\frac{2g_c}{\rho}\,\Delta P} \tag{3}$$

where:

K – flow coefficient equal to CM,
C – discharge coefficient equal to Q_a/Q_i,
g_c – conversion factor,
ΔP – pressure difference,
Q_a – actual volumetric flow rate,
Q_i – theoretical flow rate,
M – a coefficient equal to $(1-(A_2/A_1)^2)^{-1/2}$,
A_1, A_2 – cross sectional area of the pipe (A_1) and of the opening (A_2),
ρ – density.

Robert and Benedict (1984) gave semi-empirical equations in which C is dependent upon the Reynolds number *Re* and therefore on temperature. However, the idea of installing orifices at the outflows from filters is based on the correlation between linear laminar head losses in the filter bed and turbulent head losses in the orifices. The flow through drainage is often in the transition zone. As the turbulent flow is not controlled by viscosity of water the discharge coefficient is only slightly dependent on the Reynolds number:

$$\begin{aligned} &C = 1 - 3.598Re^{-0.44} && \text{for} \quad 2.5 \times 10^3 < Re < 10^6, \\ &C = 0.9975 - 0.0649Re^{-0.176} && \text{for} \quad 10^6 < Re < 10^7, \\ &C = 0.19436 + 0.152884 \ln(Re) \ln(Re)^2 + && \\ &\quad - 0.0097785 + 0.00020903 \ln(Re)^3 && \text{for} \quad 10^7 < Re. \end{aligned} \tag{4}$$

VDR filters are commonly controlled either by orifices (Cleasby 1969) or by butterfly valves (Cleasby 1989) installed at the outflow pipes. Installation at the outflow allows the pressure in the filter bed to be conserved (Cornwell et al. 1984), unlike the alternative of installation at the inflow (Arboleda 1974). When the head losses in the main distribution pipe are negligible it is assumed that the water level over all the filters is the same. This enables the flow-rate through the recently backwashed filter to be calculated (Cleasby and Di Bernardo 1980, Arboleda et al. 1985). The head loss just before backwashing is usually denoted H, and the water level fluctuations between subsequent backwashes in the plant by h_0. Just after a backwash the level of the water surface over the filters drops by h_0 and finally the following equation is satisfied (Di Bernardo 1986, 1987):

$$c_1 q_1 + c_2 q_1^{\alpha} = H - h_0 \tag{5}$$

where c_1 is a coefficient characterizing the resistance of the clean filter, c_2 and α are coefficients characterising the turbulent resistance of the orifice and the drainage, q_1 is the flow-rate through a clean filter.

The exponent α takes values of 2 (Cleasby 1989, Arboleda et al. 1985) or lower (Di Bernardo 1987) depending upon the character of the flow through the drainage. q_1 is typically between 1.3 and 1.5 times higher than the average flow through a filter and Eq. (5) is used to calculate the difference between the water levels over the filters (just after backwash) and in the clear tank, $H - h_0$. Then the water table fluctuations h_0 are to be determined to fulfil requirements considering the flow-rate through the plant, Q. Higher values of h_0 always correspond to lower plant capacity Q if the loss of water for backwashes is not considered (Dąbrowski 1991).

The water table fluctuations h_0 can be determined from one of the existing models of VDR filters. Some of them are based on deep bed filtration theory (Chaudhry 1987), but the theory is not sufficiently well developed to reliably model flocculated suspensions flow through inhomogeneous filters. Other models (Arboleda et al. 1985) use empirical equations of the coefficients, but these are valid only for the plant from which the readings were taken, and for the conditions pertaining at the time. There are also methods which do not require any unknown coefficients (Di Bernardo 1986, 1987), but these are valid only as long as the raw water quality, temperature and the plant capacity are stable. No work has been done on computing the value of the water level fluctuation, h_0, under variable conditions.

4. Practical Considerations

VDR Filter performance was investigated by examining calculations based on data collected by Cracow Municipal Company, taken from a treatment plant supplied with water from the Rudawa River. Data including the raw water temperature and peak demands, were reported between May 1990 and April 1991. The plant consisted of sixteen sand filters at that time. Because there are several other water intakes incorporated into the Cracow water supply system, the production of water from this particular plant is usually higher during dry weather, when the raw water quality is better, and so does not necessarily correlate directly with overall consumption in the town. The temperature of the pretreated water is shown in Figure 2, and the variation in viscosity normalized with respect to ν (+0°C) is shown in Figure 3. Fluctuations in flow-rate, normalized with respect to the average flow-rate, are shown in Figure 4. Figure 3 illustrates the influence of water temperature on the hydraulics of the system. Figure 5 shows relative average filtration velocity (or water demands) against relative water viscosity. There is no evidence of a strong correlation. In such a situation the design of the control system should refer to winter time (the worst situation, when the temperature of the water is the lowest and simultaneously the water demand is the largest – because of likely good quality of the raw water).

Now consider the water table fluctuations over the filters. These fluctuations are described by equation (5) with c_1 strongly temperature dependent and c_2 slightly dependent. c_1 and c_2 can by defined as referring to the whole filter or to a square metre of filter bed. The latter option was chosen so that q would be the same as the approach velocity through a filter. The filter plant operated without flow-rate controllers. Head losses in open channels distributing raw water among the filters were negligible in comparison with head losses of flow through filters. Therefore the water level above the filters could be recognized as the same at any arbitrary chosen moment. The inflows to the filters were located well below the lowest water table level. In conclusion, the construction of the plant followed the principles of VDR Filtration. However, the plant was not equipped with orifices (required to create turbulent head losses in order to control the ratio q_1/q_{avr} of the maximum flow-rate q_1 through a recently backwashed filter to an average flow rate q_{avr} in the plant). An experimentally predicted value of c_1 equal to 0.006 [(m H_2O)/(m/day)] (at +0°C) and $\alpha = 2$ for a fully turbulent flow were used in the calculations of c_2, from which the discharge coefficient directly results. Using this data the coefficient $c_2 = 0.00002$ [(m H_2O)/(m/day)^2] was calculated from Di

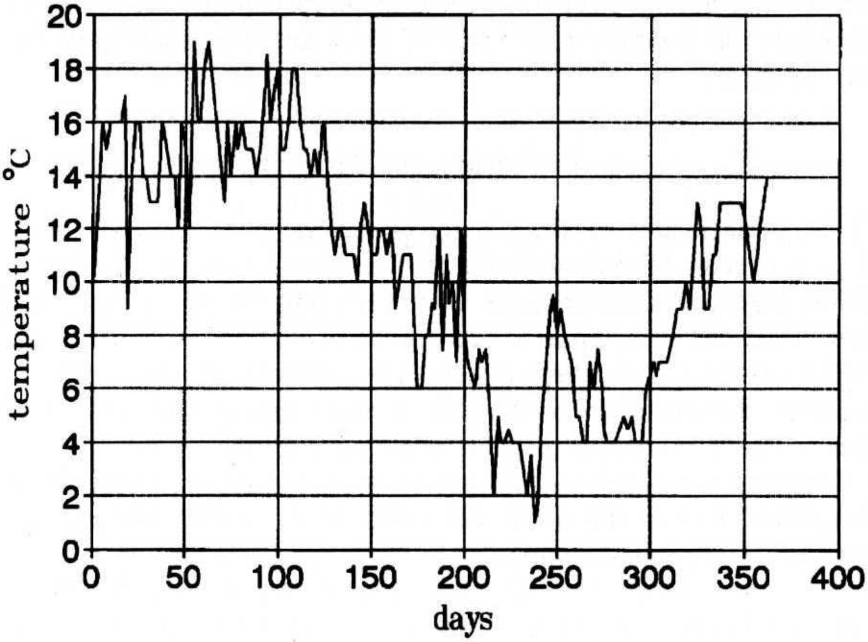

Fig. 2. Seasonal variation of temperature. Experimental data

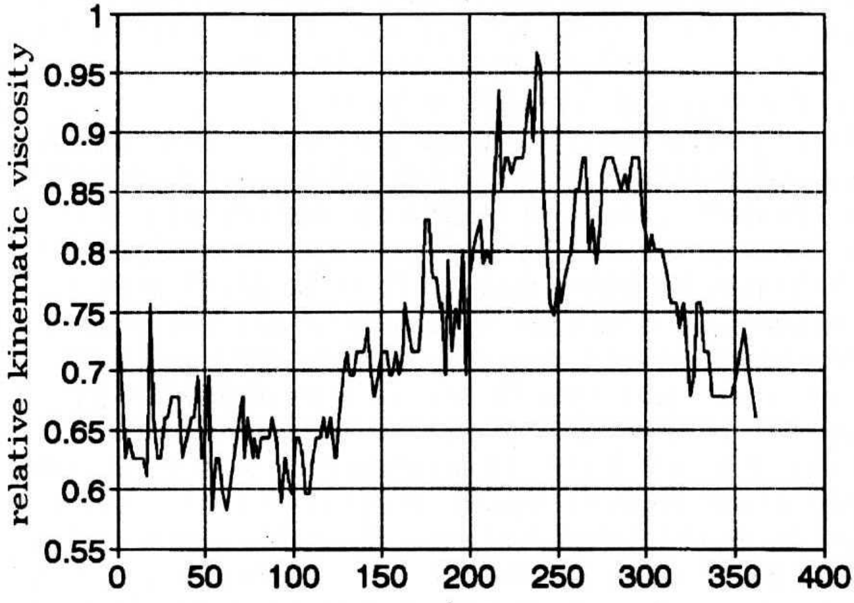

Fig. 3. Variation of relative kinematic viscosity (normalized with respect to ν (+0°C)). Results of calculations

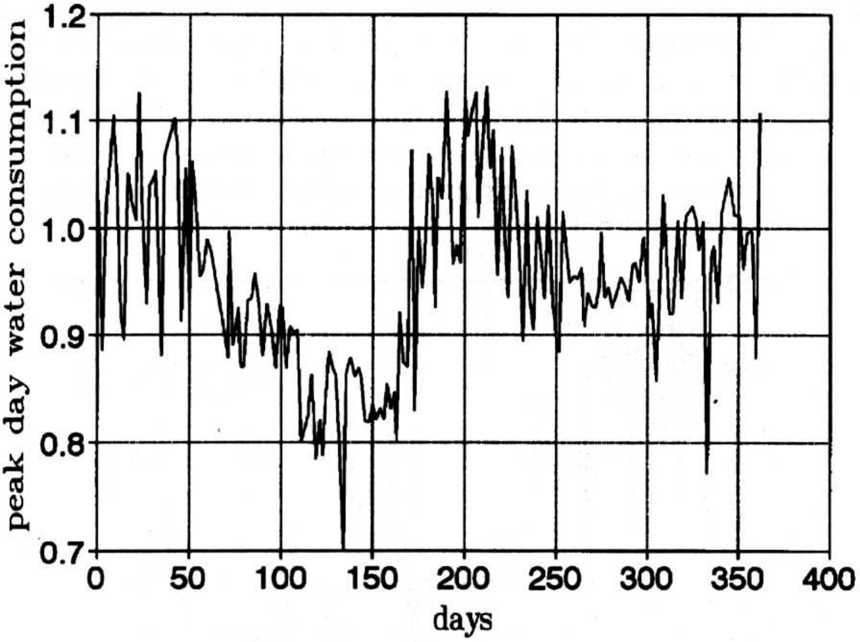

Fig. 4. Flow-rate variation, normalized with respect to average flow-rate. Experimental data

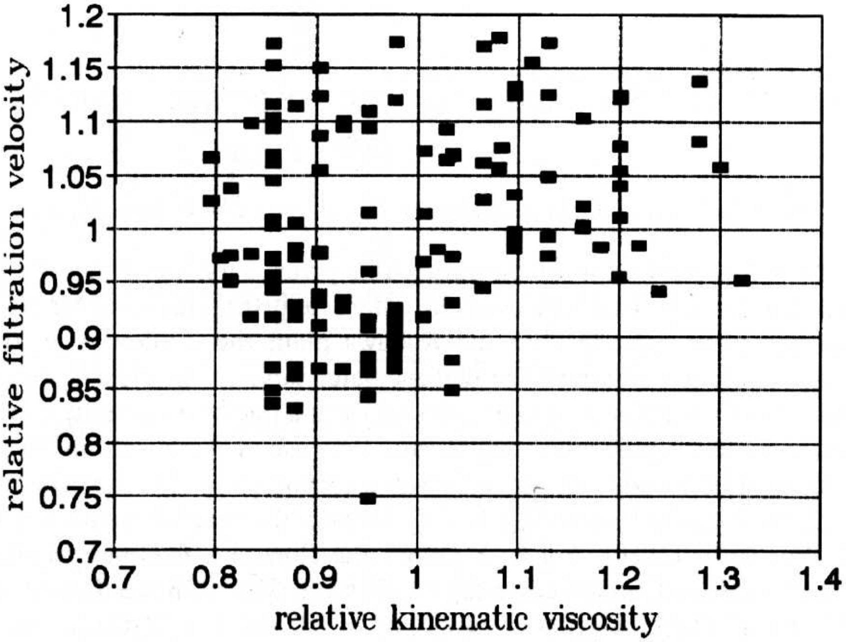

Fig. 5. Relative average filtration velocity against relative kinematic viscosity normalized with respect to ν (12°C)

Bernardo's model (Di Bernardo 1986, 1987). This coefficient characterizes the orifices required for proper filter plant operation. Discharge coefficient C calculated from equation (4), for the designed system of orifices, was very slightly affected by the water temperature, which is shown in Figure 6 for the data presented in Figure 2. In contrast the coefficient c_1, describing the resistivity of filter media to flow, is visibly influenced by the temperature, which variation is shown in Figure 7 for the data presented in Figure 2.

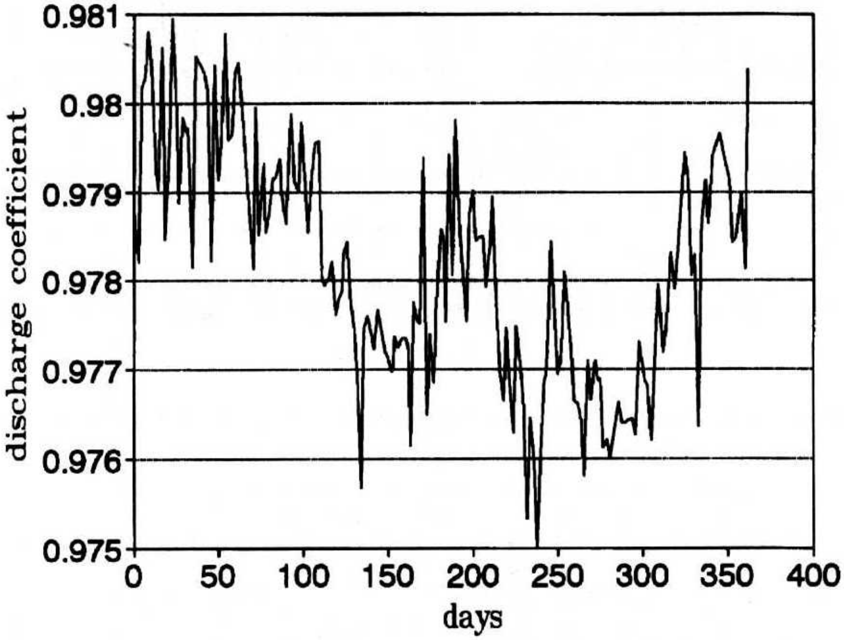

Fig. 6. Variation of discharge coefficient, C, with time. Results of calculations

There are several ways of operating the plant. First the water table level, $H - h_0$, may be kept constant over the filters, adjusting h_0 in order to achieve the required plant capacity. For the Rudawa plant the outflow from the main collecting filtrate is well above the highest water table in the clear water storage. The capacity of the plant is usually adjusted once a day by a butterfly valve that is installed at the main pipe collecting filtrate. Because of these reasons, the plant is not influenced by hourly variations in water consumption. For further advice on operating filter plants responding directly to variable water demands see Cleasby and Di Bernardo (1980). Figure 8 shows the flow-rate fluctuations through a clean filter operated under constant water level (the aforementioned value $c_1 = 0.006$ [(m H_2O)/(m/day)] (for 0+°C), $c_2 = 0.00002$ [(m H_2O)/(m/day)^2], and $\alpha = 2$ were applied in the calculations). However, it is more reasonable to avoid such changes in the filtration velocity through a clean filter because it can be proved (Dąbrowski 1994), from an economical point of view, that the flow-rate

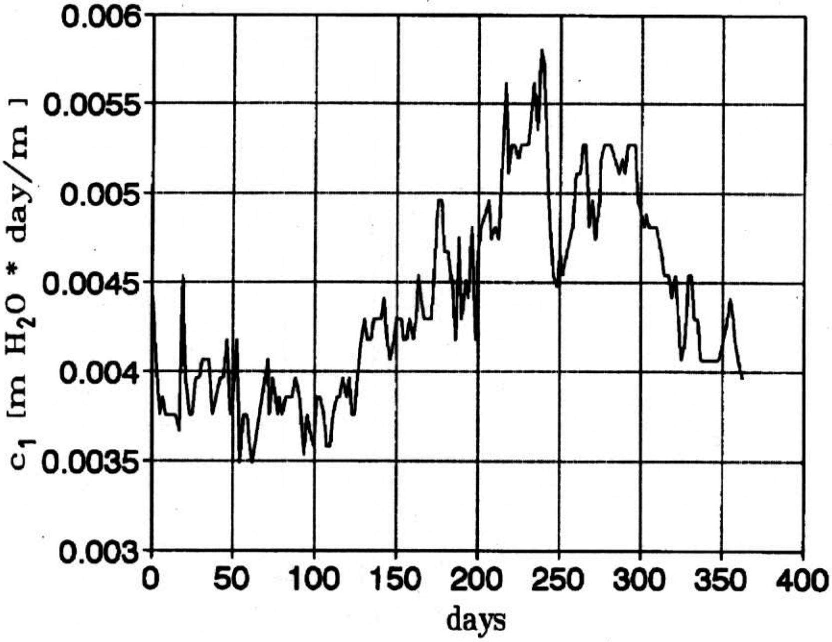

Fig. 7. Seasonal variation of c_1

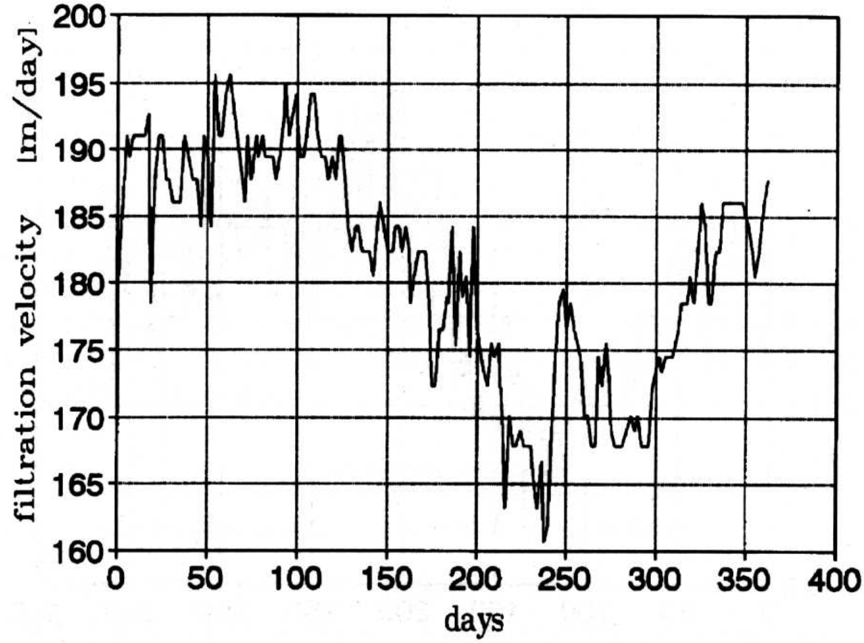

Fig. 8. Flow-rate fluctuations for a filter operated under constant water level. Results of calculations

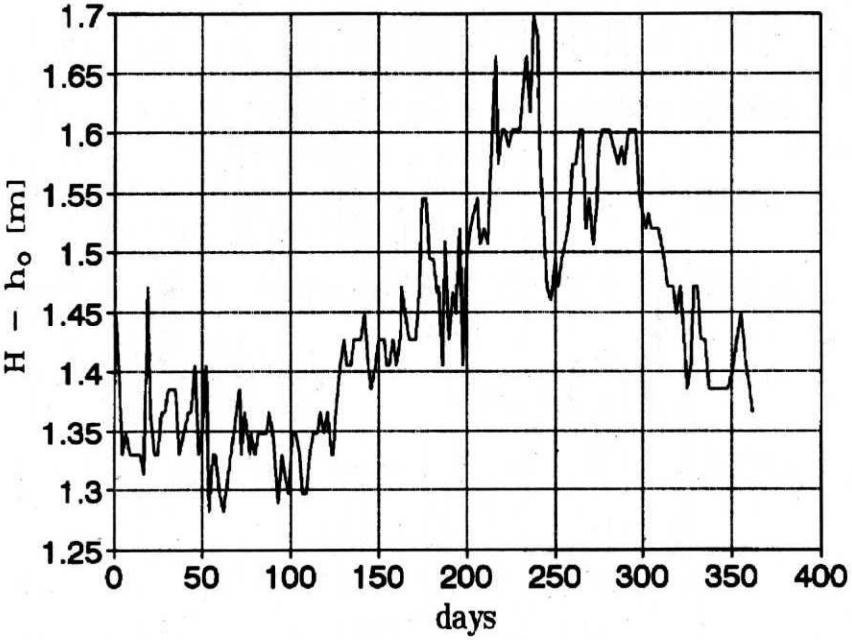

Fig. 9. Variation of water level over filter, using 1.5 × annualised average velocity. Results of calculations. Head loss $H - h_0$ is equal to the distance between the lowest water level above filters and piesometric height of water pressure in the main pipe collecting filtrate

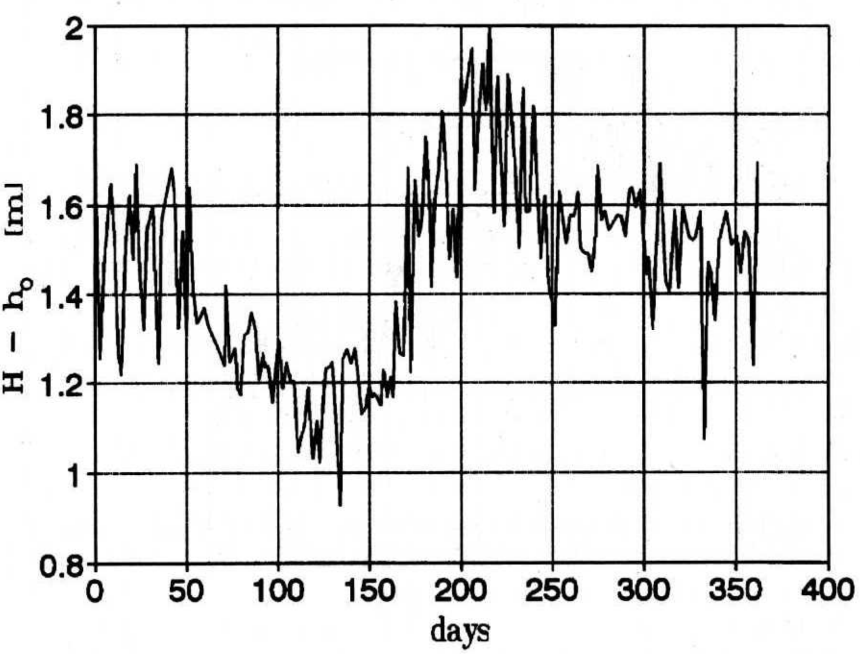

Fig. 10. Variation of water level over filter, using 1.5 × daily average filter velocity

through a clean filter should be as high as possible. The value of this flow can be determined experimentally and is dependent upon temperature. If (because of lack of specific information concerning this relationship) it is assumed that the filtration velocity through the most recently backwashed filter should be 1.5 times higher than the average velocity of the plant over the whole year, then according to the calculations the water level over the filters in the Rudawa filter plant should vary as shown in Figure 9. In these calculations, an average flow-rate through a filter q_{avr} was adjusted daily to meet water consumption shown in Figure 4, but the flow-rate q_1 through the recently backwashed filter was the same each day. It would be possible to operate the plant with such fluctuations in the water level shown in Figure 9 without a risk of uncovering the media or of flooding the plant. However, if someone assumes the same ratio (1.5) of q_1/q_{avr} and q_{avr} is a flow rate calculated each day from the water consumption in the plant, the fluctuations in the water table level above the filters are much higher (see Figure 10). Under such circumstances, the calculated water table level changes can reach an unacceptable level for the highest of the filter boxes. It follows then that this way of plant operation is not recommended, perhaps not only for this particular plant but for most VDR Filters.

5. Conclusions

Water temperature is an important factor in all water treatment processes. Because of the variable water consumption and temperature, the operation of VDR filters should be adjusted to actual conditions. The changes in water temperature and water demand reported here showed that the influence of temperature on the hydraulics of filters is substantial. If the correlation between the water consumption and temperature is not known it is advised to design the plant for winter conditions assuming the highest possible water demand. For the example discussed here the fluctuations of the filtration velocity through a clean filter were quite substantial when the water level above the filters was held constant. When the same value of the filtration velocity through a clean filter was assumed it resulted in acceptable variations in the water surface levels above the filters, resulting from unstable temperature.

Acknowledgements

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