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Optimization of a hydropower plant trash rack cleaning frequency

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ABSTRACT

The losses caused by the debris accumulated on the trash rack of a 20 MW hydropower plant aggregate were obtained and analyzed experimentally. Data for one year of operations was collected and processed. Using a simple temperature-compensated model, it was possible to distinguish clearly between the losses caused by the trash rack itself and by the debris collected on the trash rack. This made it possible to examine the seasonal effect of the debris on the head losses and to predict the optimal frequency of trash rack cleaning, as well as annual losses during electricity production and power plant economics in general. The analysis showed that the annual losses could be reduced significantly by applying an optimal cleaning strategy. However, an optimal strategy is difficult to predict, because of the stochastic nature of the amount of debris drifting daily in the river. It is much easier to perform cleaning as circumstances require by determining an optimal upper limit of head loss above which the trash rack should be cleaned. Using this approach, the total number of trash rack cleanings per year was reduced, while the extra energy losses due to debris remains unchanged.

1. INTRODUCTION

A substantial amount of debris, ice and trash drifting in a river can damage vital parts of a hydropower plant. Trash racks are, therefore, used to restrict the entrance of significantly sized material present in the water. Trash racks produce unwanted energy-losses, which can be attributed partly to debris, as well as the large-scale flow structures or eddies/vortices generated by the trash rack bars (Hribernik et al. 2013). The latter cannot be omitted. However, the losses caused by the debris collected on the trash rack can be reduced significantly when the trash rack is cleaned regularly. Debris accumulated on the trash rack does not only affect its efficacy, but it also challenges its structural integrity. Because of this, debris-removal systems are critical for trash racks. Debris is usually removed from a rack by raking, which can be done by hand or with mechanized rakes. Mechanical rakes have become the standard for large

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hydroelectric facilities; they operate by lowering the rake into the water and pulling it up the rack face. Once at the top of the rack, debris is deposited into a collection receptacle (Bradley et al. 2005). The rakes` operation can be fully automated or they can be operated manually. Regarding investment costs only, the manually operated rakes are much cheaper and usually applied on medium size hydropower plants; however, a team of workers which operate the rakes is needed and the total costs of debris removing in one year may be high when the frequency of their interventions is too high. It is, therefore, very important to find an optimal strategy for trash rack cleaning in order to keep the cleaning costs low to moderate.

Trash rack losses were analyzed for one of the three 20 MW hydropower plant aggregates . Head losses caused by the trash rack, flow rate and water temperature were measured simultaneously at 15 minute-time intervals. Data was collected and processed for one year of operation. It was possible to separate the head losses caused by the trash rack structure itself and those caused by the debris collected on it. This made it possible to isolate the seasonal effect of the debris on the head losses and to predict the optimal frequency of trash rack cleaning, as well as annual losses during electricity production and power plant economics in general.

2. TRASH RACK LOSSES

Trash rack losses are generated by trash rack bars and by the debris that is collected on the trash rack. When clean, the trash rack losses are the smallest, and they increase with the amount of trash collected on the trash rack. In order to determine the energy-losses caused by the collected trash, the energy losses of a clean trash rack need to be known.

2.1 Clean trash rack losses

Different empirical equations may be applied to predict energy losses of a clean trash rack. Kirschmer (1926) was one of the first who proposed an empirical equation for trash rack head loss:

$$\Delta h = K\left(\frac{t}{b}\right)^{\frac{4}{3}}\frac{v^2}{2g}\sin\theta \tag{1}$$

Eq. (1) considers the variable parameters such as *K* - bar shape factor, *b* - clear spacing, *t* - bar thickness, *θ* - inclination angle with channel bed, *v* - velocity through the trash rack and *g* gravitational acceleration. Eq. (1) can be applied to the bar shapes of airfoil, circular, rectangular bars and rectangular bars with rounded edges by changing the bar shape factor *K* appropriately. Many researchers adopted Kirschmer's formula till today, in order to improve it by taking into account additional influencing factors. Levin (1968) introduced blockage factor *p* (Eq. 3) and Meusburger (2001) took into account horizontal flow angle δ. There are also several other formulae available for estimating head loss through trash racks suggested by Osborn (1968), Clark et.al (2010) and Raynal et.al (2013). Raynal et.al (2013) made a comprehensive comparison of different equations and stated that, except for the case where *b*/*t* = 1, the equations proposed by

Osborn (1968), Meusburger et al. (2001), and the one proposed by himself, produced similar results. The Clark et al. (2010) equation produced good results for larger spaces between bars (*b*/*t* > 2), but did not perform well when applied to smaller spaces (*b*/*t* < 2). The head losses calculated with the Kirschmer equation (Eq. (1)) were too low in all cases. According to this, it was decided to use the Meusburger et al. (2001) equation, which can simply be adopted to account for the influence of debris accumulated on the trash rack (see next chapter) and predicts the head losses as:

$$\Delta h = K(1 + 0.65 \tan \delta) p^{1.33} \left(\frac{b}{l}\right)^{-0.43} \sin \theta \frac{v^2}{2g} \tag{2}$$

Additional to Eq. (1), this formula considers the horizontal flow angle δ, the length of the bar *l* and the blockage factor *p* defined as:

$$p = \frac{A_{RS} + A_{AH}}{A_{RF}} \tag{3}$$

where A_{RS} is the area blocked by the bars, A_{AH} the area blocked by the horizontal spacing elements and A_{RF} the total area of the trash rack field.

2.2 Clogged trash rack losses

Comparison between the theoretical head loss using Kirschmer's development and laboratory tests have found that, for a clean rack, the theory underestimated the head loss by a factor of 1.75 to 2 (Bradley et al. 2005). This factor, which is increased greatly when the rack begins to become clogged with debris, was found to be as high as 4 with 50% clogging (Bradley et al. 2005). Since the clogging, similarly to the bars and horizontal spacing element, reduces the equivalent flow area of the trash rack, its influence on head losses may simply be considered by adopting blockage factor as follows:

$$p' = \frac{A_{RS} + A_{AH} + A_{AD}}{A_{RF}} \tag{4}$$

where A_{AD} is the area blocked by the accumulated debris. By differencing Eq. (2) and (4) and combining them, one can obtain the following relationship:

$$\frac{dA_{AD}}{d\Delta h} = \frac{A_{RF}}{1.33} \left(\frac{1}{Cv^2}\right)^{\frac{1}{1.33}} \Delta h^{-\frac{0.33}{1.33}} \tag{5}$$

where *C* is the constant:

$$C = K(1 + 0.65 \tan \delta) \left(\frac{b}{l}\right)^{-0.43} \sin \theta \frac{1}{2g} \tag{6}$$

Eq. (5) determines the change of A_{AD} with the change of head loss as a function of flow velocity and head loss. It may be used efficiently to predict the percentage of trash rack clogging when head loss-time history obtained by measurements is known.

2.3 Trash rack losses` measurement

The trash rack is situated at the entrance of the inflow channel of the hydropower plant aggregate. Energy losses caused by the trash rack are categorized commonly as a head loss. Using submersible level transmitters in front of, and behind the trash rack, it is possible to measure the instantaneous head loss caused by the trash rack. Two temperature compensated *Hydrobar I* sensors with long-term stability less than 0.1% produced by Klay-Instruments (Klay Systems 2015), were applied in our case. Simultaneously, water temperature and flow rate were acquired via computer every 15 minutes and saved to the computer's hard disk. Fig. 1 shows the characteristic head loss and flow rate signals acquired during a 48 hour period. There are two long operation periods and two short periods when the aggregate stood still and flow rate was 0. Significantly high variations in the flow rate were observed during the aggregate's operation and, therefore, the variations of head loss, which changes with the second power of velocity, are even higher. Their frequency and amplitude agree well with the flow rate variations and prove that the sensors were chosen correctly and that the measurements were performed adequately.

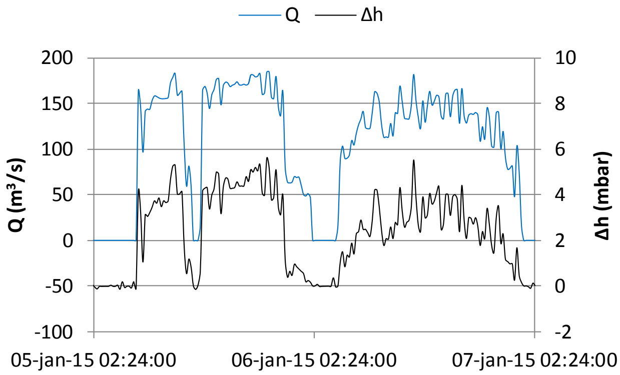

Fig. 1 Measured flow rate and trash rack loss

2.4 Seasonal variation of the trash rack losses

Trash rack losses fluctuate seasonally due to seasonal variations of flow rate and debris concentration in the river. Both are high during late spring and fall months and low during winter and summer months. Using a clean trash rack loss model (Eq. (2)) it is possible to predict the losses caused by the trash rack itself and the losses caused by the accumulated debris. In order to do this, the clean trash rack loss model should fit the data obtained during the operation with a clean trash rack. It may be assumed that the trash rack was perfectly clean after the general refit of the aggregate, which takes place once a year in wintertime. During the refit, which lasts between two and three weeks, the water is pumped out of the inflow channel and the trash rack is dismounted for any necessary repairs and cleaning. Thus, it is perfectly clean when the aggregate is assembled and put into operation again. The flow rate is low in the wintertime and almost no debris is present in the water. Therefore, the trash rack operates in a clean state for a period long enough to acquire data on its operation and adopt Eq. (2) for correct energy loss prediction of the clean trash rack. One week of data on the flow rate and head losses measured immediately after the refit were used in our case. The theoretical blockage factor *p* (Eq. (3)) was adjusted step-wise until the measured losses and those predicted by Eq. (2) fit together well (R^2>0,97). If the model is to be used during the whole year it should be temperature compensated in order to consider seasonal water temperature variations, which may influence water viscosity significantly. In February, when the general refit took place, the average water temperature was 2 ^{0}C while, in summer, the water temperature rises to 20 ^{0}C. As was shown by Hribernik (2016), temperature correction may be done simply by:

$$\Delta h = \Delta h_{ref}\sqrt{\frac{\nu_{Tref}}{\nu_T}} \tag{7}$$

where ν_{Tref} and ν_T, respectively are the water viscosity at the reference and actual temperature, respectively. Fig. 2 shows a comparison of clean trash rack head losses at the reference temperature and at 20 ^{0}C. We can see that the difference for clean trash rack head losses is up to 25% between winter and summer time, and thus should not be neglected.

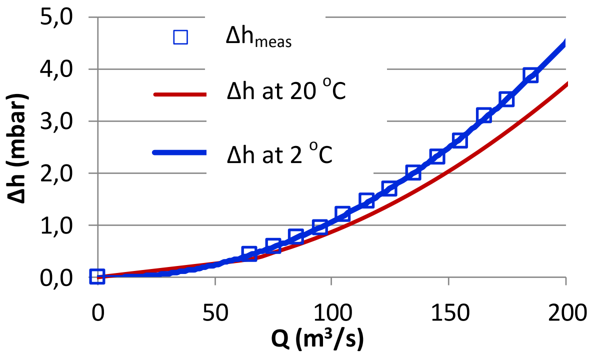

Fig. 2 Clean trash rack head losses at T_{ref} = 2 ^{0}C and at T = 20 ^{0}C

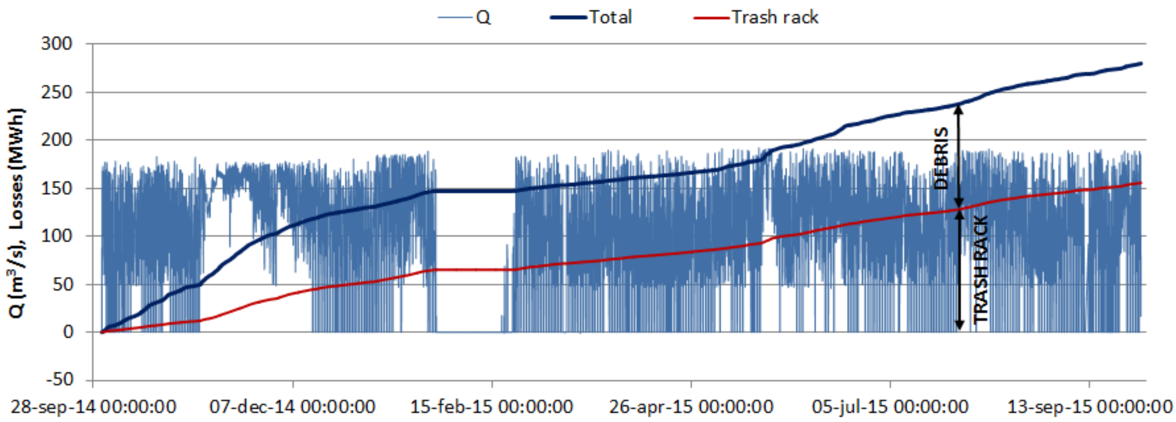

Fig. 3 Energy losses caused by a clean trash rack and by collected debris

As already mentioned, the presented clean trash rack loss model has made it possible to distinguish clearly between the losses caused by the trash rack itself and by the debris collected on the trash rack. Fig. 3 shows the cumulative one year energy losses and the variation of the flow rate. The losses are flow rate dependent, thus, the increase in cumulative losses is the highest in the autumn high water season and, at the same time, due to the high concentration of drifting trash, the influence of the collected debris on cumulative losses is the highest too. During one year of operations, debris causes up to 140 MWh of electricity losses, which is 50% of all losses, and 45% of all these losses take place in the relatively short three-month-long autumn high water period. Fig. 3 also shows that the aggregate was not operating between January 25 and February 18 when the refit took place.

3. TRASH RACK CLOGGING ANALYSIS

Trash rack clogging is a random process which is not easy to predict. However, as already mentioned, an analysis of trash rack clogging is possible if the hydropower aggregate head loss-time history is known. If we rearrange Eq. (5) as:

$$\frac{dA_{AD}}{dt} = \frac{A_{RF}}{1.33}\left(\frac{1}{Cv^2}\right)^{\frac{1}{1.33}}\frac{1}{\sqrt[4]{\Delta h}}\frac{d\Delta h}{dt} \tag{8}$$

it follows that, at the constant flow velocity *v,* the rate of growth of the area blocked by the accumulated debris $\frac{dA_{AD}}{dt}$ is proportional to the rate of growth of the head loss $\frac{d\Delta h}{dt}$ divided by the 4th root of head loss Δh and multiplied by proportionality constants. Thus, the measured head loss-time history can be split into a number of time intervals Δt, within which the head loss increase $\Delta\Delta h$ and mean head loss $\overline{\Delta h}$ at any constant flow velocity v_i are calculated and used to predict the rate of growth of the area blocked by the accumulated debris as:

$$\frac{\Delta A_{AD}}{\Delta t} = \frac{A_{RF}}{1.33}\left(\frac{1}{Cv_i^2}\right)^{\frac{1}{1.33}}\frac{1}{\sqrt[4]{\overline{\Delta h}}}\frac{\Delta\Delta h}{\Delta t} \tag{9}$$

The resulting weekly averaged rate of growth of A_{AD} is shown in Fig. 4. A one week interval was used on purpose. The trash rack was cleaned every Friday and it was possible to obtain the head loss increase $\Delta\Delta h$ per week, by comparing the head loss before and after the trash rack cleaning at any constant flow rate (flow velocity v_i). As we can see, the resulting weekly change of A_{AD} rate of growth fluctuates very randomly from week to week which proves the stochastic nature of debris flow. The general refit took place in February. Therefore, no debris was accumulated between the 5th and 7th weeks. During the first 10 weeks after the refit, debris accumulation was low. This is the winter period of low water when the concentration of debris in water is almost zero. The first spike in debris accumulation took place between the 18th and 21st weeks, which is mid-spring, when frequent rain and thunderstorms spill debris collected in surrounding forests during the winter into the river. Similar is the accumulation of debris in October (the period between the 40th and 45th weeks). The water level is high during this period, with a lot of drifting debris originating from over-flooded river banks and whole curtains of dead algae, which were blooming in the upstream reservoirs during the summer season, also appearing.

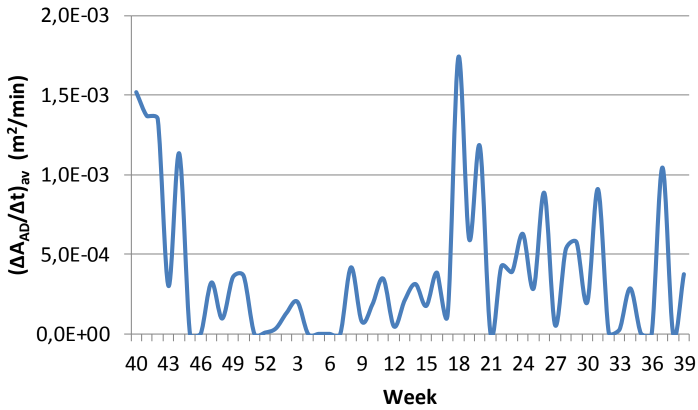

Fig. 4 Week to week change of average rate of growth of A_{AD}

4. OPTIMAL TRASH RACK CLEANING FREQUENCY

As mentioned before, the trash rack was cleaned every Friday, i.e. once a week, although the amount of collected debris was small a lot of times and did not cause any higher energy losses. It may be assumed that, in such cases, the costs of debris removal exceed the profit of the energy gain by the reduced losses. An attempt was made therefore to find an optimal strategy for economically efficient trash rack cleaning. The manually operated rakes are used on the observed hydropower plant and a team of two workers operates the rakes. The average cost of their intervention transformed into the electric energy equivalent is 17 MWh. Their intervention is, therefore, cost efficient only if the energy gain due to the cleaner trash rack exceeds 17 MWh between two successive debris removals. In order to check different strategies which may fulfil this criterion, a simple model was applied which can predict accumulation of debris between the successive debris removal. This model applies the experimentally obtained rate of growth of A_{AD} (area blocked by the accumulated debris) presented in Fig. 4 and discussed in previous chapter. It is possible to predict the instantaneous A_{AD} simply by integrating its rate of growth in time and starting with A_{AD} = 0 each time the debris was removed from the trash rack. The results of this model are presented in Fig. 5. An upper limit of head loss (Δh_{lim} = 8.3 mbar at 180 m^3/s), which should not be exceeded, dictated when the cleaning intervention had to be carried out. Simulation started on February 19 after the completion of the hydropower aggregate refit, when the trash rack was clean. Only one trash rack cleaning was necessary to keep the head loss below the upper limit until May 2, while 4 interventions were necessary in May, with the second and third only three days apart. In June and July, the debris was removed two times, while in August and September cleaning took place once per month. Altogether, only 11 cleaning interventions were necessary to keep the cumulative energy losses at the same level as during actual operation with 4 interventions per month i.e. 30 interventions in total. If we compare the actual and simulated head loss (Fig. 5), we can see that, during the first two months of operation, the simulated head loss exceeds the actual one, thus, simulated cumulative losses increased faster. However, better ordered interventions in May and June reduced the difference and, at the end of September, both simulated and actual cumulative energy losses were almost the same. This shows that the correct timing is more important than the total number of cleaning interventions. It happened four times in May and June that the actual trash rack cleaning was executed too late (only by a day or two) which caused the head losses to increase drastically (see marked area in Fig. 5) and moreover increased the actual cumulative energy losses to the level of simulated energy losses.

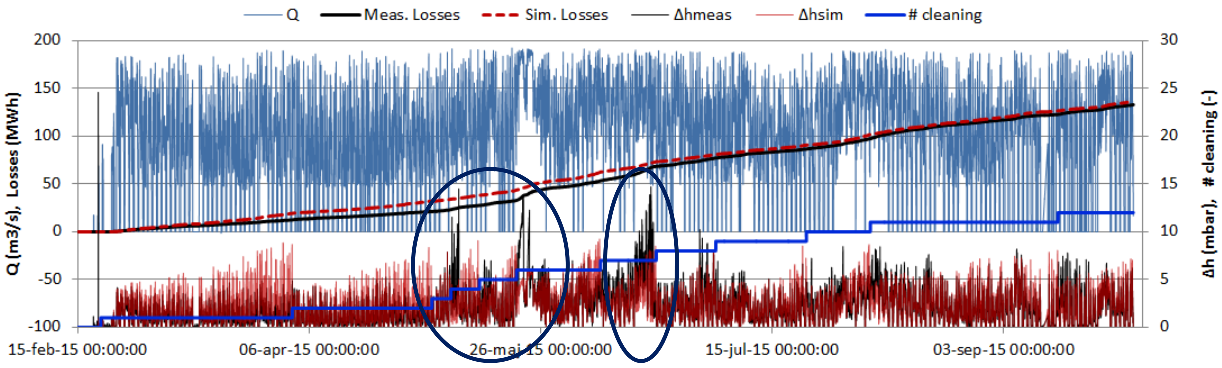

Fig. 5 Comparison of actual and simulated head losses ($\Delta h_{lim,sim}$ = 8.3 mbar at 180 m^3/s)

It has already been demonstrated how it is possible to reduce the number of trash rack cleaning interventions and, at the same time, keep the cumulative energy losses almost unchanged, thus, how to operate more cost efficiently. In the next step, the same model was applied to predict the optimal number of cleaning interventions at which the sum of debris caused energy losses and cleaning expenses expressed as energy equivalent was at its minimum. To do this, the upper limit of head loss was simply changed step by step in an interval between 6.0 mbar and 23.0 mbar and the head loss predictions were carried out as the one presented in Fig. 5. The obtained results are shown in Fig. 6. The number of necessary cleaning interventions reduced from 18 to 4 and, at the same time, the debris caused energy losses increased from 26.9 MWh to 164.5 MWh as the upper limit of head loss increased from 6.0 mbar to 23.0 mbar. However, if we observe the sum of both expressed as an electric energy equivalent, we see that it reduces from 332.9 MWh to 200 MWh and then raises again to 232.5 MWh. Thus, there is a minimum. The minimum is not clearly distinctive and the optimal upper limit of head loss may lie between 10 mbar and 15 mbar, which makes the final decision not easy. However, since the differences in total energy equivalent are very small within this interval, it is advisable to choose its lower value at which the maximum amount of debris accumulated on the trash rack, as well as the mechanical load implied on the trash rack, is smaller.

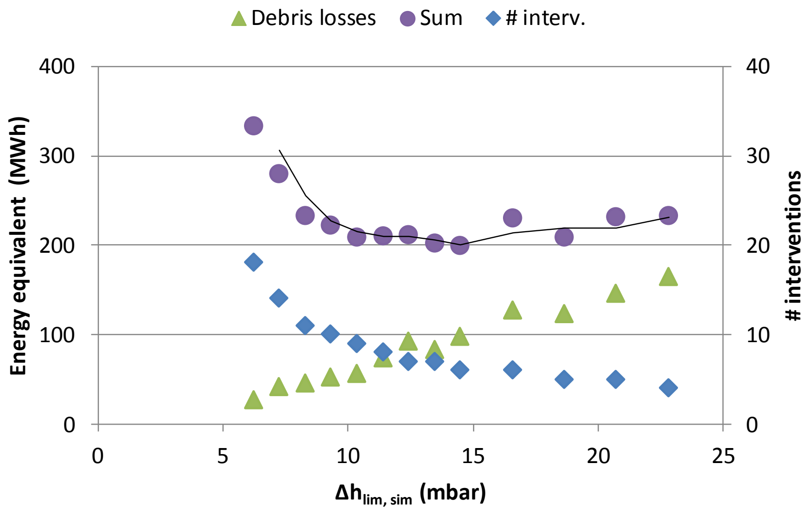

Fig. 6 Simulated energy losses

5. CONCLUSIONS

Trash rack losses of a 20 MW hydropower aggregate were measured and analyzed during one year of operation. They were separated into the losses caused by the clean rack and accumulated debris, respectively. Although the trash rack was cleaned regularly, the cleaning was performed once a week, the collected debris increased the annual energy losses by 100%. A simple model was, therefore, proposed to study different trash rack cleaning strategies. The experimentally obtained data on rate of debris accumulation growth used within this model makes it possible to simulate instantaneous blockage of the flow area caused by the debris accumulation on the trash rack, and to predict the corresponding increase of trash rack head loss. The latter is at its minimum immediately after the debris removal and grows until the upper head loss limit is reached and the trash rack is cleaned again. Simulations show that the existent trash rack cleaning practice (once a week) was not efficient, although the invested effort (number of cleaning interventions) was very high. The same results may be obtained with less effort i.e. only 35 % of all cleaning interventions, if the trash rack is not cleaned before the upper limit of head loss (Δh_{lim} = 8.3 mbar at 180 m^3/s) is reached. It was also shown how to find the optimal upper limit of head loss in order to minimize the sum of debris caused energy losses and the energy equivalent of the expenses spent on trash rack cleaning. Using this approach, the total number of trash rack cleanings per year may be reduced even more. However, mechanical load implied on the trash rack should also be considered. Thus, reserved cleaning strategies are more reasonable.

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