Operational Optimization of Reverse Osmosis Plant Using MPC

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This article is devoted to the study of optimal control strategies for reverse osmosis membrane modules with recirculation. To develop a control system, a reverse osmosis membrane model, previously developed, is used. In detail, this work studies the membrane module with recirculation, investigates the possibility of controlling the impurities concentration in the permeate using an advanced control strategy and, finally, proposes a solution to optimize the recycling time through the use of model predictive control.

1. Introduction

Water purification plants based on reverse osmosis (RO) membranes are widely used both for sewage water purification from harmful impurities and for silicon electroplating and in the concentration of mixtures of many types (production of juices).

To improve the efficiency of RO modules, different operating modes and different ways to incorporate the module in the technological scheme are possible. To increase the saturation of the concentrate and thus increase the flow of permeate from the feed solution (water), the usage of a membrane module with recirculation is proposed. However, when operating the module, there arises the problem of optimizing the recycling time, at the end of which expiration the membrane must be rinsed and drained.

In order to study and develop control systems for these kind of units, it is necessary to build a mathematical model of the membrane module. In recent years more and more research papers devoted to the development of mathematical models of reverse osmosis membranes have been published. The article of Assef et al. (1995) is devoted to an experimental investigation of constrained model predictive control (CMPC) for a reverse osmosis (RO) desalination unit. The article of Absar et al. (2008) deals with the development of a simplified model of a reverse osmosis membrane which is used to investigate the effectiveness of the hollow fiber. The article of Bartman et al. (2009) is devoted to the development of a model-based nonlinear control system, where the model of the reverse osmosis membrane is obtained from experimental data. Article Sobana et al. (2014) is devoted to the development of control systems reverse osmosis module using the centralized and decentralized techniques. Two control strategies are adopted, namely, multiloop internal model control–proportional integral controller (IMC-PI) under centralized scheme and multivariable PI controller with decoupler under decentralized scheme.

This article proposes a control system reverse osmosis module with recycle using model predictive control (MPC) approach. The proposed system will affect not only the high-pressure pump but also to on the drain valves in the feedback, allowing to optimize the time of recycling. Unlike most works devoted to the reverse osmosis membrane, the membrane model is designed not for a specific object (using the experimental data), and obtained on the basis of physical laws.

Application of MPC approach for optimizing the recirculation time, will improve the performance of the membrane modules, and reduce wear. MPC approach can be widely used in the industry, because it provides the technical and economic benefits.

2. The proposed technological scheme for water purification with recirculation

A key prerequisite for the optimization and management of any process is to create a mathematical description and mathematical models of the basic units included in its layout. A mathematical model of a reverse osmosis membrane was presented earlier in the article of Nadezhdin et al. (2015).

In this article the authors propose a process for water purification using reverse osmosis membrane elements. A simplified flow diagram of this process is shown in Figure 1. The process layout includes three tanks: a feed tank, one designed for draining retentate and one for draining permeate. Moreover, it also contains a reverse osmosis membrane module and a high pressure pump. The level of the feed water (V_f) in the feed tank is continuously controlled, as to avoid possible leakages due to excessive fill. With the help of the high-pressure pump, feed water is pumped to the pressure (P_f) and supplied to the input of the membrane module. The impurity concentration in the feed water (C_f) is constantly changing due to the fact that some impurities leave the permeate (C_p) or are deposited on part of the membrane, as well as due to the inlet impurity concentration (C_{in}), referred to the stream entering the feed tank for maintaining level (Q_{in}). The impurity concentration in the permeate (C_p) and the retentate (C_r) and the volumetric flow rate of permeate (Q_p) and retentate (Q_r) at the outlet of the membrane module define the operating conditions of the membrane module itself and can be controlled trough the pressure at the membrane inlet and the recycle time.
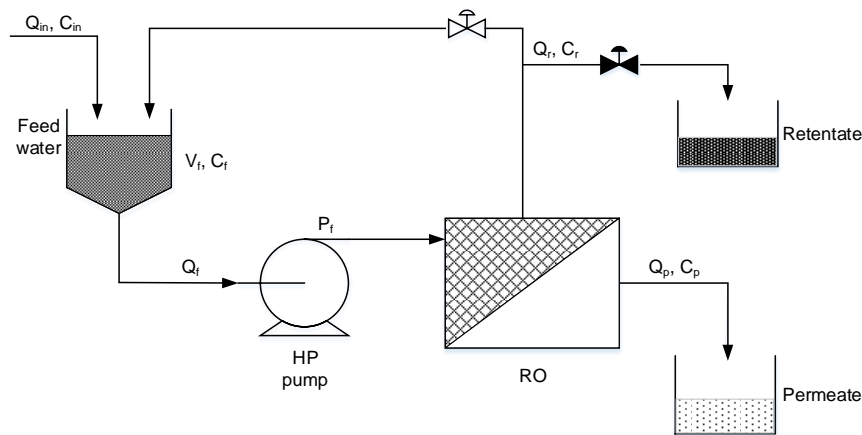

Figure 1: The proposed process scheme including a RO membrane module

In order to model the filtration process and develop a control system for the membrane module, it is necessary to build a mathematical model of the plant shown in Figure 1. The mathematical description of the membrane module was developed earlier. To determine the change in the feed water level in the feed tank, the following material balance equation can be used:

$$dV_f/dt = Q_{in} - Q_f + Q_r$$
$$Q_f = Q_r + Q_p$$
(1)

By integrating this expression with respect to time, the level of the feed water (V_f) in the tank can be computed. Instead, to determine the change with time in the impurity concentration one can use the following equation:

$$dC_f/dt = C_f^0 + \frac{Q_{in} \cdot C_{in} - Q_f \cdot C_f + Q_r \cdot C_r}{V_f}$$
(2)

In Eq(2), C_f^0 is the initial concentration of impurities in the feed water. The impurity concentration in the retentate is determined thanks to Eq(3):

$$Q_f \cdot C_f = Q_r \cdot C_r + Q_p \cdot C_p$$

$$C_r = \frac{Q_f \cdot C_f - Q_p \cdot C_p}{Q_r}$$

(3)

The developed mathematical model of the process shown in Figure 1 has been implemented in the package MATLAB / Simulink. Some simulation results are presented in Figure 2, where the volumetric flow of permeate (Q_p) and retentate (Q_r) at the membrane outlet as well as the impurity concentration in the permeate (C_p) are reported. As seen from the graphs in Figure 2, during the operation of the reverse osmosis membrane module in the proposed process scheme with recycle, eventually the permeate flow tends to zero. This is due to the fact that supersaturation of the feed water occurs, in consequence of which the membrane element becomes clogged, permeate flux output decreases and the concentration of harmful substances in the permeate (C_p) increases. The increase in the impurity concentration in the permeate is shown in Figure 2, the change in concentration is presented in relative units. At a certain instant, the membrane is no longer able to filter and requires flushing to be cleaned.
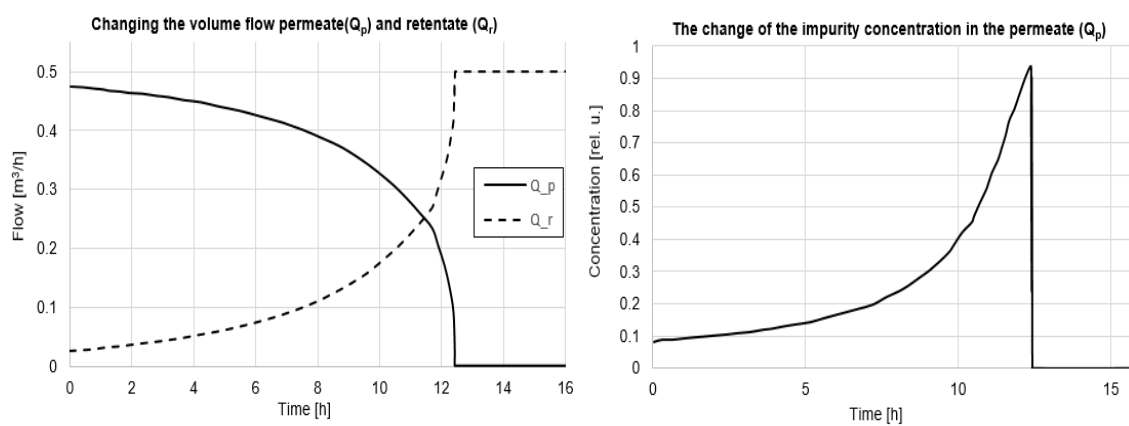

Figure 2: The simulation results

To ensure the normal operation of the proposed scheme with recycling, it is necessary to develop a control system that maintains the permeate flow at the outlet of the membrane module and the concentration of harmful substances in it at a certain required level.

3. Development of a control system for the RO membrane module with recycle

To control the proposed process scheme with recycle, a control system consisting of two control loops is selcted (Figure 3).
The first control loop regulates the volumetric flow of the permeate at the outlet of the membrane module, acting on the pump and regulating the pressure at the module inlet. A second loop is used to regulate the concentration of impurities in the permeate through the opening position of the drain valve and the valve in the recycle loop. The control action on the valves are generated based on the sensor readings, providing a comprehensive integrated assessment of the impurities in the permeate.
As already pointed out, the first control loop adjusts the the permeate flow at the outlet of the module (Figure 3) by changing the pressure at the memebrane inlet. The development of such control systems has already been addressed in the work of Nadezhdin et al. (2015). The setting of the MPC controller was made based on existing applied research on MPC controllers for different chemical processes, set out in the paper from Manenti (2011). This paper compares two control schemes: PID and MPC. Based on these studies, it was shown that MPC has a less rough impact on the membrane, thereby increasing its expected life.
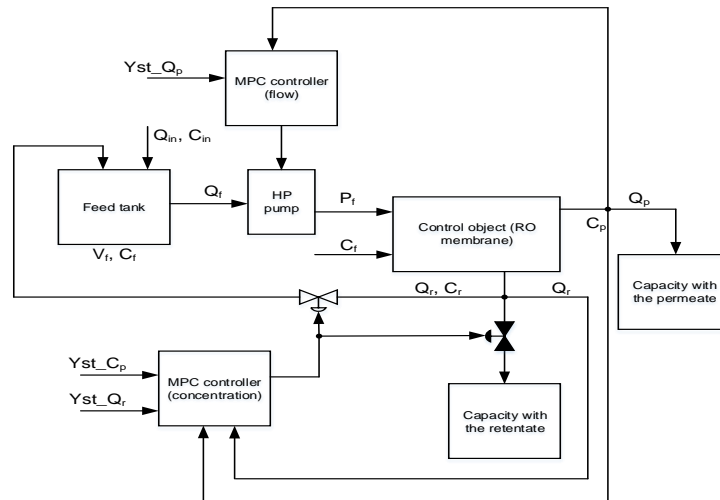
Figure 3: Control system for a RO module with recycle

A loop to control the pressure at the membrane inlet, based on the outlet permeate flux, has been implemented. As a result, process transients like those shown in Figure 4 are obtained.
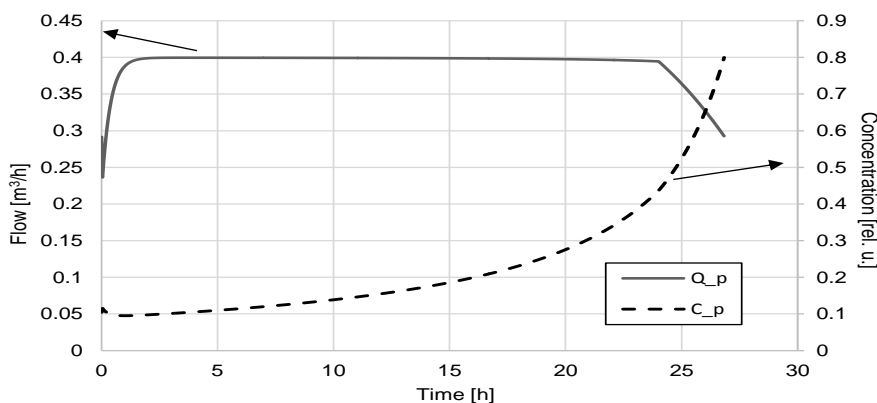

Figure 4: Changes in the volumetric flow of permeate (Q_p) and impurity concentration (C_p), when the "flow" control loop is activated

As can be seen from the graphs presented in Figure 4, as time passes by, MPC controller can not cope with the retention of the volumetric flow of permeate at the right level, in the presence of recycle. The volumetric flow rate of the permeate is maintained at a predetermined level until a certain point due to the MPC controller that adjusts the operation of the pump. The concentration of impurities is constantly growing in the permeate and retentate. Upon reaching the maximum concentration of impurities in the feed water, and given that the membrane gets clogged by impurities, the outlet permeate flow tends to zero.

Thus, there is a need to include a second control loop. The second control loop will be aimed at holding the concentration of harmful impurities in the permeate at a given level. For this reason, the control of impurities in the permeate is realized using a modern sensor, which takes measurements of integral indicators of water quality. On the basis of the data coming from this sensor, the controller, which directly operates the valves, will be triggered. Valves are always in the reverse mode, if one is open, the other one is closed. Thereby, their opening level must be dyamically regulated depending on the harmful impurities concentration in the permeate.

As a regulator, it is possible to use a relay with a dead zone or a MPC controller. The principle of operation of the regulator based on a relay is as follows: when the impurity concentration in the permeate reaches a certain level, the drain valve opens and the valve in the recirculation loop closes. Thus, the enriched feed water strarts to wash the membrane element, as long as the level of harmful substances in the permeate reaches the alllowed lower bound concentration. As soon as the impurity concentration in the permeate

drops to the desired level, the relay restarts operating, thus closing the drain valve and opening the valve in the recirculation loop.

As a result of the inclusion of the "concentration" loop, using a controller based on a relay, transients like those represented in Figure 5 are achieved. As seen from these graphs, the inclusion of the second control loop enables to keep the concentration of impurities in the permeate inside a certain range and the permeate flow volume at a certain level.
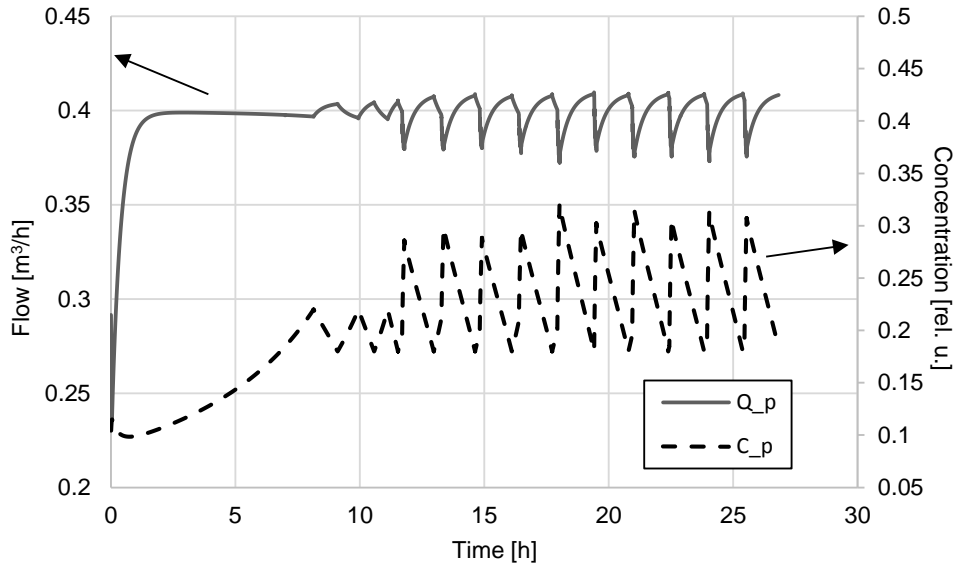

Figure 5: Changes in the volumetric flow of permeate (Q_p) and impurity concentration (C_p), when two control loops (MPC controller and relay) are active

The graphs in Figure 5 show that at the time of 11 h, there is a strong perturbation. Such disturbance is caused by an increase in the impurity concentration of the feed water. Thus, the level of contaminants in the permeate increases too, due to the fact that each membrane has a certain selectivity coefficient. In other words, each membrane does not reject a certain percentage of contaminating substance, i.e. with the increase of impurities in the feed water, also the impurity in the permeate has to grow. Also, at time of 17.5 h, the concentration of impurities in the feed water entering the feed tank is increased again, thus creating an additional disturbance. As shown in Figure 4 and Figure 5 concentration increases disproportionately with the flow. This is because in the first two hours the clean membrane transmits less the dissolved impurities. Therefore, the increase of impurities in the permeate is slower than the increase in the permeate. Unlike the relay controller, MPC controller allows not only to control the concentration of impurities in the permeate (C_p), but also to optimize the time of recycling. The input variables for the MPC controller are the retentate flow rate (Q_r) at the outlet of the membrane module and the impurity concentration in the permeate (C_p). By minimizing the functional (4), the MPC approach allows to find the optimal value of Q_r and C_p, which must be maintained.

$$f = \begin{cases} Q_r \to \min \\ C_p \to \min \end{cases} \tag{4}$$

Thus, a minimum concentration of impurities in the permeate and a retentate minimum flow can be enforced. As a result of the inclusion of the "concentration" loop, but using this time a MPC controller, the transients shown in Figure 6 are obtained. As seen from these graphs, the inclusion of the second loop using a MPC controller also allows keeping the impurities in the permeate at a certain level. On the whole, the proposed control system fulfills its main task, i.e. that of maintaining the volumetric flow of permeate at a precise and constant value. When imposing perturbations such as changes of the impurity concentration in the feed water, the permeate flow experinces deviations from its set-point but these deviation are not critical. Moreover, by using the MPC approach, the concentration of impurities in the permeate and retentate flow can be minimized. The retentate flow was 2.5 m^3 for 24 h, when using the controller based on the relay while when using a MPC controller, it is lower (2.2 m^3). Thereby MPC is demosntrated to be

more effective than the relay-based regulator. Also, it provides a certain secure range of impurity concentration in the permeate. The task of maintaining the impurity concentration in the permeate at a certain level is difficult. It is feasible by including several membrane modules for a more subtle purification of the feed water.
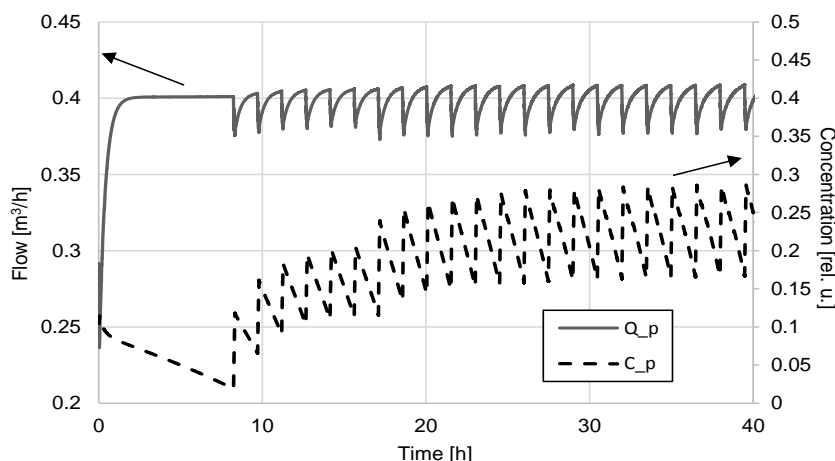

Figure 6: Changes in the volumetric flow of permeate (Qp) and impurity concentration (Cp), when two control loops (based on two MPC controllers) are activated

4. Conclusions

An automatic control system is developed for the proposed process of water treatment with recycle. A control system consisting of two loops is built. One loop regulates the flow of permeate by adjusting the operation of a pump that imposes the pressure at the inlet of the membrane module. A second loop controls the impurity concentration in the permeate through a dynamic control of the recycling rate. The regulation of the impurity concentration in the permeate is possible using a relay with a dead zone and a MPC controller. The MPC approach minimizes the concentration of impurities in the permeate and retentate flow, thereby being more effective and reliable that the relay-based regulator. In the future, a control system for cascade reverse osmosis membranes by means of MPC will be developed.

Acknowledgment

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