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Guidelines for hydraulic analysis of treatment plants equipped with ultrafiltration and reverse osmosis membranes

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ABSTRACT

Despite all recent developments to improve the hydraulic performance of components in ultrafiltration and reverse osmosis plants, from advanced membrane modules to complex energy recovery devices, only little attention is being paid to enhance the plant operation as a fully integrated system. In practice, different hydraulic devices are chosen based on their individual performances without considering associated hydraulic interactions among the devices. This becomes a matter of concern, especially during transient events when a change in the operation of one device may lead to unacceptable pressure and flow rate fluctuations through the plant and eventually costly damages. Although several excellent books have been written on fluid transients for pipeline systems, there is still a need for a guideline on the hydraulic analysis of ultrafiltration and reverse osmosis plants which include complex and vulnerable hydraulic components such as UF and RO membranes, energy recovery devices, and solenoid valves. This study provides a guideline for the integrated hydraulic design of plants with a focus on modeling of UF and RO units, which leads to a more robust, reliable, and water-tight system.

Keywords: Ultrafiltration; Reverse osmosis; Desalination and treatment plants; Transient flow; Hydraulic analysis; Water hammer

1. Introduction

The importance of high-quality drinking water for public health and production processes makes water treatment and desalination plants crucial infrastructure elements. Water scarcity is estimated to affect one in three people on every continent of the globe, and almost one-fifth of the world's population live in areas where water is physically scarce [1]. Due to stressed groundwater resources and growing demand for water, intensified by population growth, urbanization, climate change impacts, and increases in household and industrial uses, the number of water treatment and desalination plants is constantly rising [2].

The plants are designed such that they can operate several decades safely and efficiently and meet future demands. One crucial aspect of the design of a plant is the hydraulic performance. Several modeling techniques and hydraulic programs have been developed to assess the steady-state behavior of hydraulic systems [3,4]. These programs provide information about

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head loss, flow rate, salinity, and water chemical content during steady operations. However, predicting the hydraulic response of the systems to transient events occurring between steady-state conditions is not straightforward and requires a detailed knowledge about the hydraulics of the systems.

The transient events lead to water hammer phenomenon, which in extreme cases, drastically harms hydraulic components such as pipes and pumps [5–7]. UF modules are in particular prone to the pressure fluctuations during water hammer which might cause a considerable reduction in lifetime of filtration fibers or even their massive breakage [8–10]. The UF fibers are also susceptible to excessive transmembrane pressure induced by the transient events [8]. Hence, the adverse effects of these events need to be minimized to avoid unnecessary maintenance and costs. Apart from the integrity of hydraulic components, the performance of the system during transient events, for example an optimized procedure for switching between filtration to backwash, is a deterministic factor for the efficiency of the water production and power consumption. Last but not least, controlled transient events (e.g. generating pressure spikes of about 0.1 barg) have been suggested to be deployed as a mechanism to reduce the fouling of UF systems during normal operation that eventually leads to an increase in the water production [11].

Therefore, a proper understanding of the transient behavior of the hydraulic systems is essential for a proper design of a plant. Several excellent books have been written on the fluid transients in pipeline systems [12–14]. These books focus on the water hammer phenomenon, anti-surge devices, and transient numerical modeling; they furnish a good groundwork for understanding of the flow transients. However, they do not provide any guidance as a framework for conducting a hydraulic transient analysis. A practical guidance on the hydraulic analysis of pipeline systems has been recently established [15]. However, it has specifically targeted water transportation systems (WTS) and water distribution systems (WDS) that are much larger in size compared to water treatment plants and do not include complex components such as UF and RO membranes, nor typical plant operations.

This study is aimed to expand the existing guideline [15] to desalination and treatments plants by including a correct modeling of UF and RO units in the hydraulic analysis and by considering the common transient events occurring in the plants. After introduction of a modeling approach and critical scenarios, a practical example of the modeling and analysis of a plant is presented to show how a proper hydraulic transient analysis ensures the safety and hydraulic integrity of the hydraulic systems and contributes to a cost-effective and energy saving operation.

2. Method

2.1. A systematic approach to transient hydraulic analysis

Before starting the hydraulic analysis, a clear procedure needs to be defined that specifies the type of required activities and their order based on their importance and relevance. The flow chart in Fig. 1 shows a systematic approach to the hydraulic analysis for WTS and WDS systems [15]. This approach is applicable to UF/RO plants, since from the hydraulic point of view, the only differences between these systems are in the size and complexity of the components.

2.2. Hydraulic analysis

The hydraulic analysis is performed by numerically investigating the hydraulic behavior under different transient scenarios. This requires a numerical model which includes all relevant hydraulic components. There are several one-dimensional water hammer commercial packages available (as summarized in Ghidaoui et al. [16]) that enable engineers to build the hydraulic models of pipeline systems and to simulate the transient behavior. Detailed explanations of the governing equations and the numerical approach deployed in these packages are available in standard texts [12–14].

2.2.1. Hydraulic subsystems

A treatment plant consists of various hydraulic systems that are connected to each other with pipes, valves, and other hydraulic connections. Considering the whole plant for the hydraulic analysis is a computationally intensive endeavor and for large plants might be impossible. A more practical approach is to divide the plant into hydraulically disconnected systems (hereafter called subsystems) which have no hydraulic interaction. The "hydraulically disconnected" means that no pressure transient in one subsystem travels to the other subsystems and vice versa. There are two common conditions where subsystems are hydraulically disconnected:

(1) Subsystems are disconnected by closed valves.
(2) There are basins (large tanks) located between the subsystems.

An example of the first condition is the feed and backwash systems in UF/RO units. During the feed

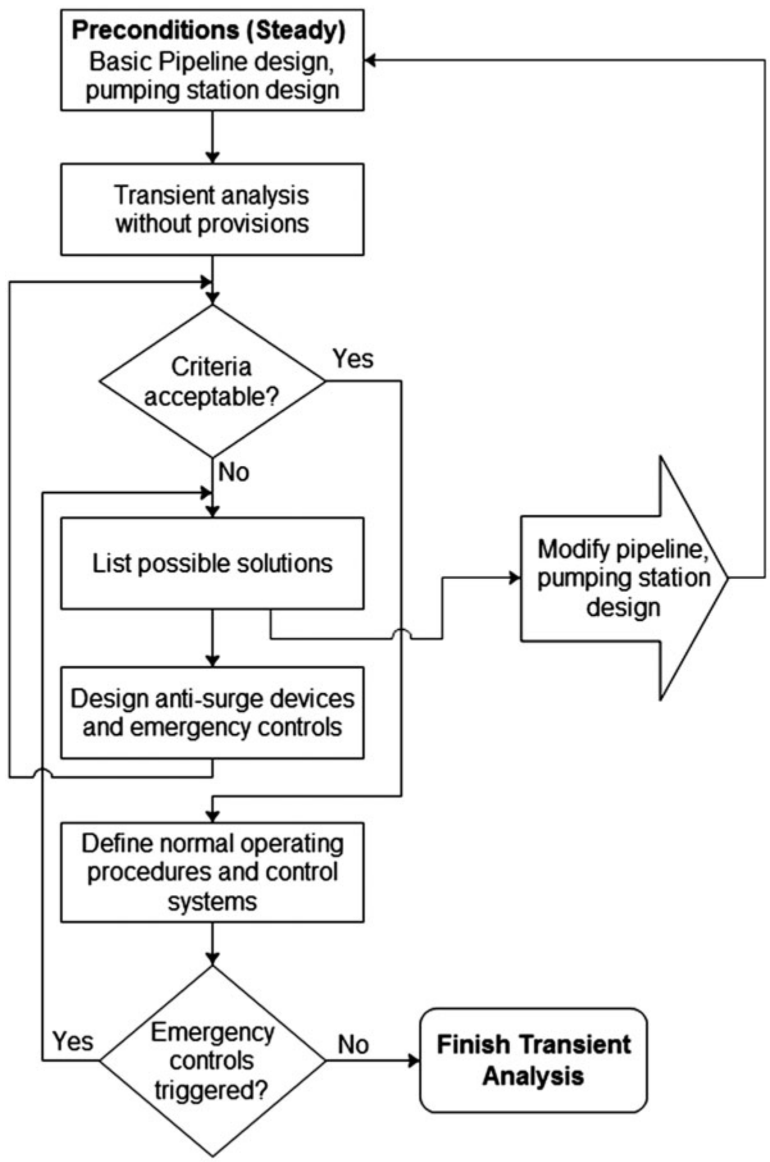

Fig. 1. A systematic approach for the hydraulic analysis [15].

process, modules are disconnected from backwash system by closed backwash valves. Therefore, it is possible to separate the unit to two independent hydraulic subsystems: feed and backwash. Similarly, other subsystems such as clean-in-place and chemically enhanced backwash are defined. Raw water tank is a good example for the second condition where a tank isolates the UF unit from upstream screening systems.

2.2.2. Cascade approach

After introducing smaller subsystems, each subsystem needs to be numerically modeled. Subsystems themselves can consist of thousands of components. Encompassing all components in one numerical model dramatically hinders the robustness of the numerical program and significantly increases the computational time. This leads to difficulties, especially in large plants with thousands of UF and RO filtration modules. Therefore, a proper modeling approach is required to simplify the numerical model without affecting end results. Instead of including all small details in one large numerical model, it is possible to build smaller numerical models, extract their relevant hydraulic properties, and then insert these properties in larger models. In this way, a numerical model with a relatively small number of components is built that correctly represents the hydraulic behavior of the plant.

For example, in a filtration unit with 40 UF skids each having 40 modules, a numerical model with at least 1,600 components is needed to represent all UF modules (without considering all other components such as pumps and valves). Instead, using a "cascade" approach, three models are built, namely modules, skids, and filtration unit with 1, 40, and 40 components, respectively. The hydraulic properties of one module are calculated and transferred to the skid in the form of an "equivalent element". Similarly, each skid is represented by one equivalent element as schematically depicted in Fig. 2. Thus, the final model for the filtration unit only contains 40 components.

The equivalent element needs to consist of a pipe and a resistance to correctly represent the water hammer response and head losses of the system. The resistance ensures that the head loss of the equivalent element is the same as the total head losses of the represented system. The head losses are due to the following reasons:

(1) Hydraulic losses due to the bends in pipes, valves, diffuser, etc. These head losses have a quadratic relation with the discharge.
(2) Membrane losses caused by the passage of the water through the membrane. These head losses linearly change with flow assuming a laminar flow through membranes [17].
(3) Required pressure to overcome the osmotic pressure in first and second RO stages. This pressure is independent of discharge and is related to the solvent concentration [18].

Thus, the head loss and discharge relation for the total resistance is a second-degree polynomial given in Eq. (1):

$$\Delta H = aQ^2 + bQ + c \tag{1}$$

where ΔH and Q are the head loss and the discharge, and a, b, and c are constants. In order to obtain the coefficients a and b, the total head loss for several discharges (from zero up to the maximum discharge) are calculated and then a second-degree polynomial is fitted through the data points. This fitted function gives the coefficients for the equivalent resistance. For UF modules, the c value is zero while for RO modules it is calculated based on the solvent concentration.

The pipe in the equivalent element ensures that the water hammer characteristics of the represented system, namely pressure wave traveling time and the water hammer storage, are maintained. This concept has been successfully used for schematization of large networks [19]. In the following, a brief explanation is provided to show how an equivalent pipe represents the correct transient behavior of a group of pipes.

During a transient event, pressure, p, and velocity, v, in the pipeline system change according to the mass and momentum water hammer equations [12–14]:

$$\rho c^2 \frac{\partial v}{\partial x} + \frac{\partial p}{\partial t} = 0 \tag{2a}$$

$$\rho \frac{\partial v}{\partial t} + \frac{\partial p}{\partial x} + \frac{4}{D}\ \tau_w = 0 \tag{2b}$$

in which x and t are the spatial and temporal coordinates, ρ is the fluid mass density, D is the pipe diameter, τ_w is shear stress at the pipe wall, and c is the pressure wave speed which depends on the bulk modulus elasticity of the fluid, the density of the fluid, the elastic modulus of the pipe, the pipe internal diameter, the pipe wall thickness, and dimensionless parameter related to the pipe constraint condition. For a fast transient event, the maximum magnitude of the pressure change can be derived from Eq. (2a) as [12,13]:

$$\Delta p = \rho c\ \Delta v \tag{3}$$

For simplicity, Eq. (3) is transformed to the relation between the head changes, ΔH, and the discharge changes, ΔQ:

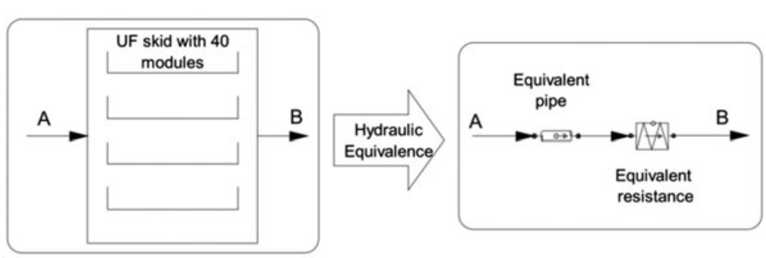

Fig. 2. Equivalent element representing a UF skid.

$$\Delta H = \frac{c\Delta Q}{gA} \tag{4}$$

with g as the gravitational acceleration and A as the pipe cross section. The time that the pressure wave travels the full length of the pipe, L, is:

$$T = \frac{L}{c} \tag{5}$$

By inserting Eq. (4) into Eq. (5), the amount of water zvolume that is stored in a pipe during the water hammer (so-called the water hammer storage, V) is calculated:

$$V = \Delta Q \times T = \frac{gA\ \Delta HL}{c^2} \tag{6}$$

As a simple example, a UF skid with M modules is considered. All modules have the same geometry and are installed in a parallel configuration. By choosing a length and a wave speed for the equivalent pipe (L_{eq} and c_{eq}) equal to those of modules (L_{mod} and c_{mod}), the condition for the traveling time is satisfied. The second condition (i.e. the equivalent water hammer storage) requires:

$$\left(\frac{gA\Delta H}{c^2}\right)_{eq} = \sum_{1}^{M}\left(\frac{gA\Delta HL}{c^2}\right)_{mod} \tag{7}$$

Considering parallel configuration of the modules, the head variation over each module is equal to the total head change over the skid. Thus, Eq. (7) is further simplified to Eq. (8). Therefore, the equivalent pipe has a length, cross section, and wave speed of L_{mod}, A_{eq}, and c_{mod}, respectively.

$$A_{eq} = \sum_{1}^{M} A_{mod} \tag{8}$$

It has to be noted that in the above-mentioned example, the length of the feed and permeate distributor of the skid is not considered in the calculation of the traveling time of the pressure wave. In reality, the pressure wave passes through the top modules shortly later than the bottom modules, since it first propagates through the header. Thus, due to the existence of the distributors, the configuration of the modules is not exactly parallel and there is a time difference in the propagation of the pressure wave. However, this difference is much smaller than the span of events that occur during transient period. For example, considering a feed and permeate distributor with a length of 5 m, the wave travels 10 m more for the top module compared to the bottom one. Supposing wave celerity of 1,000 m/s, the total traveling time difference in this case is 0.01 s. This is marginal in contrast with the response of the hydraulic components which takes place in order of seconds. Therefore, the overall solution for the transient behavior of the system is not importantly affected by assuming a parallel configuration.

2.3. Critical scenarios

The critical scenarios are defined as the transient events that cause harmful pressure transients. Based on the nature of the transient events, a difference is made between transient emergency events such as pump trip and unintentional valve closure and transient normal events such as plant start-up and shutdown. The former events occur abruptly, for example due to the power failure or valve malfunctions, and might put the system in serious danger because of the consequent extreme pressures or velocities. However, the latter cases are usually less critical regarding the safety of the system. Nonetheless, they take place on a more frequent basis and can considerably impact the efficiency of the system with respect to the water production and energy consumption. Fig. 3 illustrates the scenarios that are essential in the transient hydraulic analysis of plants.

2.4. Acceptance criteria

In the evaluation of a transient event, pressure is the most critical parameter. There are also other relevant parameters, depending on the type of hydraulic components, which must be taken into account such as a minimum fluid level in air vessels, maximum velocity in pipes, and maximum air pressure during air release from air valves. Respective criteria for common hydraulic components are usually provided by manufactures or obtained according to international standards [15]. However, up to the knowledge of the authors, there is no standard that specifies an acceptance criterion for filtration membranes.

It has been experimentally shown that reduction in pressure fluctuations using “slow valves” and a slow pump start-up/shutdown procedure decreases the membrane failure [9]. However, no value for the amplitude of the allowable pressure has been reported. In several other studies, the harm of water

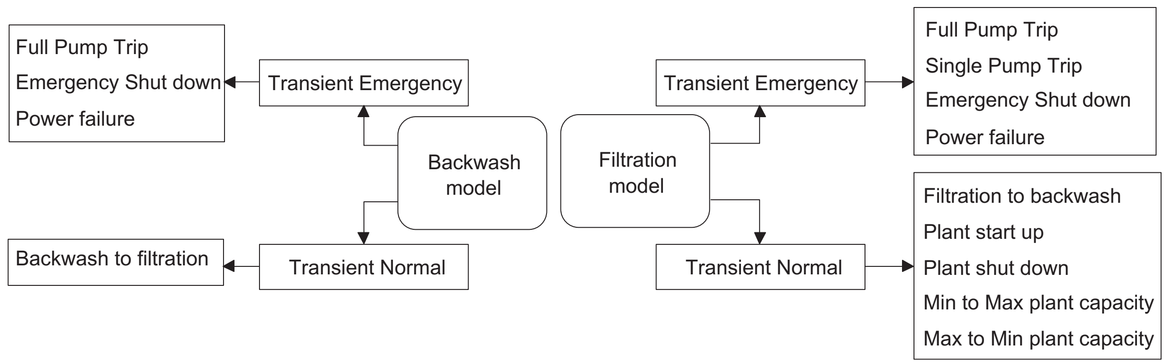

Fig. 3. Critical transient scenarios in a plant.

hammer to membranes has been acknowledged [8,10], but still no criterion has been given.

Another condition that causes the membrane failure is the presence of air [8]. By accumulation of air in a membrane, air cushions are formed that may give shocks when the pressure is changed at the transition from filtration to backwash. Therefore, situations of sub-pressure leading to the air intrusion should be prevented by a proper system design. For the hydraulic analysis presented in this study, the occurrence of the negative pressure is considered as the only unacceptable criterion for the membranes.

3. Materials

A desalination plant with a capacity of 100 million cubic meters of freshwater a year is studied. The desalination plant consists of a pre-treatment system, seawater reverse osmosis (SWRO) unit, brackish water reverse osmosis (BWRO) unit, and post-treatment facilities. The seawater is pumped from raw seawater tank through the disk filters and UF modules, and then flows to the SWRO unit for further purification. Part of the filtered water from UF unit is directly pressurized by the SWRO pumps and fed to the RO membranes. The other part is sent to the energy recovery devices where the pressure of the RO brine is transferred to the UF permeate stream. Using a booster pump, the pressurized permeate water is passed through the SWRO skids. The brackish water from the SWRO unit retreated in the BWRO unit and then transferred for post-treatment. Fig. 4 depicts a schematic view of the model. The upstream boundary of the model is the raw seawater tank and the downstream boundary is the post-treatment facilities. The BWRO unit is not included in the model, since there is a large tank between the SWRO and BWRO units which ensures a constant head upstream of BWRO unit and makes these units hydraulically disconnected from each other during transient events (as explained in Section 2.2).

For performing the hydraulic analysis of the system, a numerical model of the system is built in the experimentally validated water hammer program Wanda 4.0 [20]. All relevant hydraulic components such as pumps, valves, and pipes are included in the model. The cascade approach is utilized to model UF and RO skids.

4. Results and discussion

All scenarios shown in Fig. 3 are important regarding the water hammer effects and need to be checked during hydraulic analysis. Here, only three scenarios are presented to show the effects of fluid transients on the hydraulic system. During the analysis, first initial design (ID) of the plant is assessed and then, if necessary, proper modifications are recommended and verified.

4.1. Scenario 1: power failure during filtration

Due to a power cut, all electrical equipment fails. Fig. 5 shows the speed and discharge of a low-pressure pump (LPP) and a SWRO pump after the incident. As it is seen in the figure, the discharge through the LPP and SWRO pumps dramatically drops, and it becomes zero after about 2 and 0.5 s when the downstream check valves close.

By closure of the check valve downstream of the LPP, no feed water is supplied from the raw seawater tank to the UF skids. While the discharge of permeate water from UF skids becomes almost zero (solid line in Fig. 6), the balance tower, which is installed as a surge protection device between UF and SWRO unit, starts to charge the SWRO unit (see dotted and

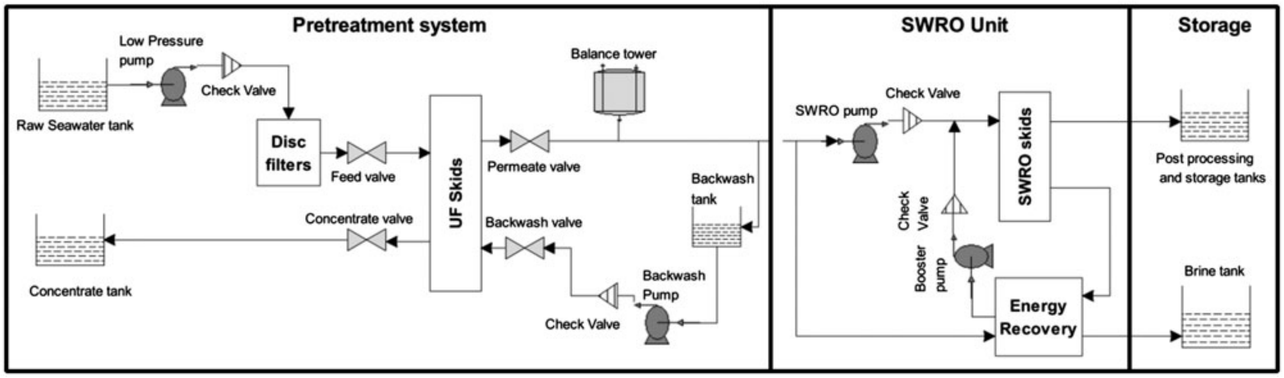

Fig. 4. Schematic view of hydraulic model for a desalination plant.

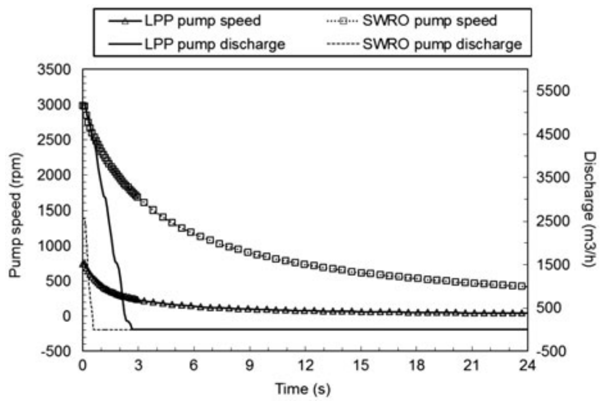

Fig. 5. Pump speed and discharge time series of a LPP and a SWRO pump.

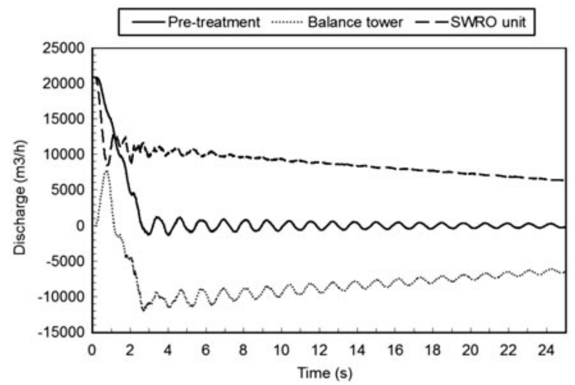

Fig. 6. Times series of the total discharge in pre-treatment system, balance tower and SWRO unit.

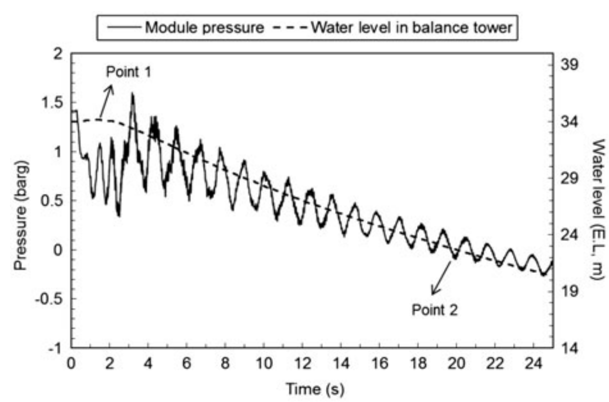

Fig. 7. Time series of pressure at module and water level in balance tower.

dashed line in Fig. 6). This is due to the fact that the water level in the tower is higher than the SWRO manifold and the brine tank level. All water from the balance tower flows to the brine tank through the ERD, since other flow passages are blocked due to the closure of check valves in SWRO unit.

Fig. 7 shows the pressure at the highest elevated UF module and the water height in the balance tower. Initially, the water head in the balance tower increases (as indicated by point 1 in Fig. 7). Due to the check valve closure downstream of the SWRO pump, all flow toward the SWRO unit enters ERD which results in a sudden deceleration of the approaching flow from pre-treatment system, and consequently increase in the pressure upstream of the SWRO unit. This pressure increase is absorbed by the balance tower, so water level in the tower slightly increases.

After about 2 s, when all check valves are closed, the pressure in the pre-treatment system becomes a function of the water level in the balance tower (static pressure) plus the pressure fluctuation due to the travel of pressure wave between the balance tower and the check valve of the LPP pump (solid line in Fig. 7). Simulation shows that 20 s after the power failure, the water level in the balance tower becomes equal to the height of highest elevated UF module, and therefore, a negative pressure is observed in the UF module (point 2 in Fig. 7). Further discharge to the SWRO unit increases the negative pressure in the modules. Hence, it is recommended to consider a closure mechanism for a main line valve (manually or with backup power) before this critical time of 20 s to avoid any negative pressure in the modules.

4.2. Scenario 2: emergency shutdown of backwash model

There are two sets of valves installed at the concentrate tank in the backwash system of the pre-treatment unit: one set for the chemical section and one set for the non-chemical section of the tank. According to the ID, it is possible to close both valves simultaneously. The full stroke closure time (FSCT) of these valves is 15 s as shown by the dashed line in Fig. 8. The simultaneous closure of these valves leads to a sudden increase in the pressure from 2 to 7 barg (as indicated by the solid line in the figure). This pressure rise might not only harm the membranes, but also violate the pressure criterion for other components such as pipes and membrane housings where the maximum allowable pressure is below 7 barg.

Based on the results of the simulation, it is recommended that during normal operation the chemical and non-chemical valves are set in a reverse mode which means if one set starts closing, the other set is forced to opening. Using this mechanism, the FSCT of the valves is reduced to 7 s which increases the total efficiency of the system. Moreover, the pressure hardly changes due to a sudden closure of one set of valves (as illustrated by the dotted line in Fig. 8). This means that the safety of the systems is ensured without any need for expensive high-pressure-rate pipes and components.

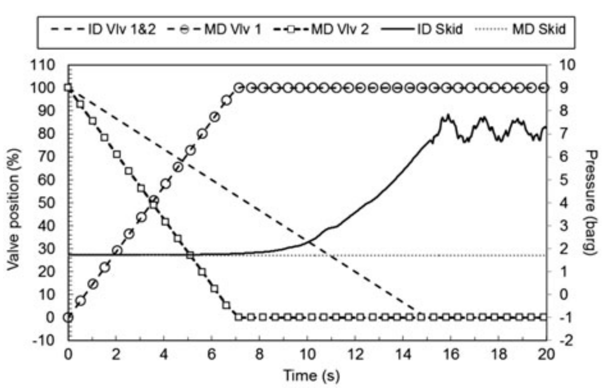

Fig. 8. Time series of valve closure and consequent pressure at the highest modules of UF skids for ID and modified design.

4.3. Scenario 3: switch over backwash to filtration for UF skids

After cleaning the modules of the UF skid with a reverse flow, the backwash procedure stops. The backwash pump slows down and then trips. Moreover, the backwash and concentrate valves at the skid close and the skid is prepared for filtration procedure. In the ID, the backwash pump shuts down without any provisions. This causes a significant pressure drop in the backwash pipeline profile and a negative pressure of about −0.4 barg occurs at highly located modules of the skid as shown in Fig. 9.

Therefore, the following modifications are inserted to avoid the negative pressure in the skids:

(1) The height of the siphon at the inlet of the concentrate tank is increased by 1.7 m. Therefore, a higher back pressure is provided in the backwash profile. The increase in the back pressure is limited to the pump capacity and power consumption consideration.
(2) An additional valve is installed in the main backwash pipeline profile between the skids and concentrate tank. This valve is always open except during the backwash shutdown procedure. When the backwash pump starts to slow down, this valve closes, and consequently, the pressure in the pipeline profile increases. It is suggested that this valve becomes mechanically limited to 20% closing angle (see the dashed line in Fig. 10) to avoid any over pressure in case of unintentional valve closure.

As it is shown in Fig. 9, the minimum pressure after the shutdown is 0.4 barg higher than that of the ID. By implementing the above-mentioned recommendations,

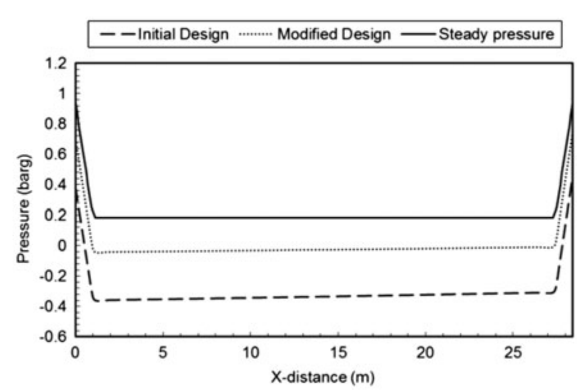

Fig. 9. Minimum pressure in the highest module during switch over condition.

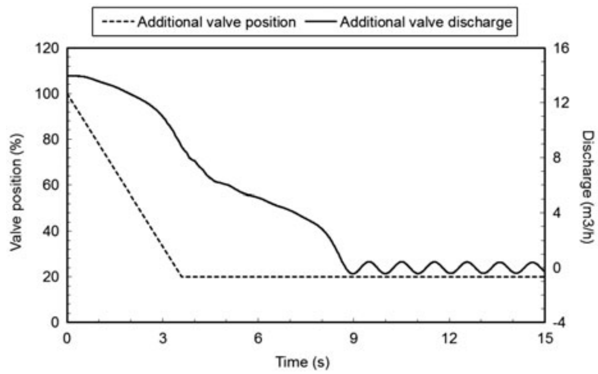

Fig. 10. Time series of valve position and discharge for the additional valve.

the whole shutdown procedure takes place in about 10 s without harmful negative pressures in the skid. Minimizing the shutdown time means less permeate water is consumed which leads to an increase in the water productivity of the system. Moreover, the safety of the modules is ensured by avoiding negative pressures.

5. Conclusions

A general guideline for performing hydraulic analysis of desalination and treatment plants was provided. By introducing a cascade approach, a robust hydraulic model of the plant was built that represented the transient behavior of the plant. Through a case study, the performance of hydraulic systems in a desalination plant was assessed. During emergency transient events, harmful negative pressures and large pressure fluctuations were observed. Therefore, protective measures were suggested in order to ensure the safety of the system. It was shown that by implementing these measures to the piping system and the control units of the plant, the adverse hydraulic effects of water hammer phenomenon can be minimized.

The modeling approach deployed in this study has been based on the hydraulic knowledge and understanding of transient flow behavior. For intricate components such as UF and RO modules, there is no experimental data available that can be used to verify the applied approach. The effect of the membrane on the wave celerity, the flow regime in the modules during transient events, and the alteration of the fiber resistance under transient flow are some of the aspects that add to the complexity of the transient response of UF and RO modules. Therefore, an experimental investigation to the module transient response can provide useful information that enables plant designers to perform an accurate hydraulic analysis. Moreover, combining such investigation with an autopsy and failure analysis of membranes can result in introducing a criterion for admissible transient pressure.

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