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Introducing pre-pressurization/depressurization grooves to diminish flow fluctuations of a rotary energy recovery device: Numerical simulation and validating experiment

Yue Wang [a,b,c,*], Yawei Duan [a,b,c], Jie Zhou [a,b,c], Shichang Xu [a,b], Shichang Wang [a,b]

[a] Chemical Engineering Research Center, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China
[b] Tianjin Key Laboratory of Membrane Science and Desalination Technology, Tianjin 300072, China
[c] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, China

HIGHLIGHTS

- Pre-pressurizing/depressurizing grooves were typically introduced into the RERD.
- The flow fluctuation of the slotted RERD was largely reduced about 75.3–77.2%.
- The pressure variation of the slotted RERD was greatly reduced about 90.7–92.5%.
- Correlative error between simulative and experimental results was less than 7.55%.

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ABSTRACT

In order to diminish the flow fluctuations of the rotary energy recovery device (RERD), the pre-pressurization and pre-depressurization grooves were introduced and typically slotted on the surface of the RERD's endcovers. Effects of the grooves on performance fluctuations of the RERD were researched by means of computational fluid dynamics (CFD) simulations and validating experiments. Simulative results indicated that when compared with the un-slotted RERD under flow rate of $12 m^3/h$, rotary speed of 400 rpm, and operating pressure of 6.0 MPa, the flow fluctuation amplitudes of the slotted RERD were reduced about 75.3% for high pressure outlet and 77.2% for low pressure outlet respectively. Similarly, the pressure fluctuation amplitudes of the slotted RERD were dramatically reduced about 92.5% for high pressure outlet and 90.7% for low pressure outlet. In addition, the validating experiments were conducted under the same operating conditions. The results showed that flow fluctuation amplitudes of experiments were in good agreement with that of the simulations, and the difference between them were about 2.76–7.55%, verifying the simulation model was reasonable. Thus, it provides a feasible and effective way to use the pre-pressurization and pre-depressurization grooves to diminish the flow fluctuations of the RERD.

1. Introduction

With the accumulative development of membrane technology over the past years [1–3], seawater reverse osmosis (SWRO) has got many researchers' interest to provide economic and effective measures to achieve high quality fresh water. Energy recovery device (ERD), one of the core components of SWRO desalination system, has a great significance on reducing the cost of seawater desalination. Up to now, there exist two patterns of ERD, one is the isobaric ERD, and the other is centrifugal ERD [4–6]. The former can achieve a higher efficiency since it transforms the pressure energy directly based on the theory of positive displacement, which has been the hotspot in this research field [7].

Nowadays, there are two kinds of isobaric ERDs following the positive displacement principle, including rotary energy recovery devices (RERDs) like the PX and piston-type pressure exchangers like the DWEER [8,9]. In this paper, the research work was on basis of a typical RERD as seen in Fig.1, which includes three key components, the brine endcover on the left, the rotor in the middle, and the seawater endcover on the right. Two symmetrically distributed ports were embodied in the seawater endcover, one high pressure port for outgoing high pressure seawater (HP-OUT) and one low pressure port for incoming low pressure seawater (LP-IN). The brine endcover has a same structure as the seawater endcover, except that two ports are for outgoing low pressure brine (LP-OUT) and incoming high pressure brine (HP-IN), respectively.

* Corresponding author at: Chemical Engineering Research Center, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China.
E-mail address: tdwy75@tju.edu.cn (Y. Wang).

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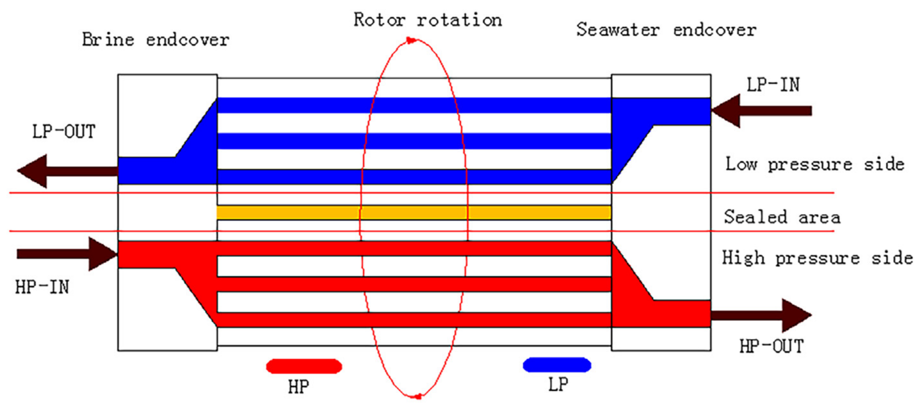

Fig. 1. The schematic diagram of the RERD.

The rotor containing 12 axial ducts arrayed in a circle, which is the sole rotation component of the device [10].

During operation, about half of the ducts communicate with low pressure stream and the remaining dusts connect with the high pressure stream. The hydraulic energy is transferred from the high pressure brine to the low pressure seawater by the way of direct and momentary contact in the rotor ducts. With the rotation of the rotor, the ducts go through a sealing region in the endcovers which separates the low and high pressure stream [11–13].

As the rotor makes one complete revolution, the pressure of each duct changes twice, that is from low pressure to high pressure and then to low pressure again. Since the difference is so large between the low pressure level and high pressure level, significant flow and pressure fluctuations may arise accompanying the rotating of the device. According to the working principle, the most possible occasion that generates the fluctuations is when one pressurized duct begins to communicate with the low pressure port, or one depressurized duct begins to connect with the high pressure port of the endcovers. Great pressure difference between the duct and the corresponding pressure port may induce significant flow and pressure fluctuations for both the inlets and outlets of the device, which are harmful to the stability of RERD itself and SWRO desalination system as well. However, till now, the developing mechanism of the flow fluctuations of the RERD still remains unclear, and appropriate measures to mitigate the fluctuations have been seldom researched and discussed.

As is known, the RERD has a similar operating principle as the axial-piston pump, and its pressurizing process corresponds to the loading stroke of the pump, while the depressurizing process correlates to the suction stroke of the pump. In addition, the core need for the two devices is in common, that should be the continuity and the stability of the flows. According to this logic, some consequence concerning the flow ripple of the high pressure pump may also apply to the RERD.

In the past years, many researchers focused on solving the flow ripple and cylinder pressure transient problems of axial-piston pump by introducing silencing grooves in valve plates. B. Helgestad [14] provided a method for calculating cylinder pressure in axial-piston hydraulic pumps with or without silencing grooves, and he thought that the rate of pressure rose and fell could be controlled by applying the grooves on the plate. J.M. Bergada [15] researched the relationship between the flow loss and pressure/flow dynamics in an axial-piston pump. He established a model with quickly calculating speed and high quality, which could be used to simulate the output pressure and flow ripple of the axial-piston pump in detail. Refs [16–19]. developed the mathematical model of delivery flow of an axial-piston pump with conical cylinder blocks and investigated the effect of a silencing groove on the flow characteristics of the pump. C. Guan [20] applied the pre-pressurization fluid path on the axial-piston pump's valve plate to study the effects of it on the flow fluctuation and instantaneous pressure in the piston chamber by method of theoretical analysis and computational fluid dynamic (CFD). The results show that the pre-pressurization path reduces the pressure difference between the discharge port and the piston chamber which is believed to be the main cause of the flow ripple. The above literatures indicate that flow ripple of the axial-piston pump can be reduced with the help of grooves in valve plates. It is believed feasible to adopt groove structure into the endcovers of the RERD to deal with the similar problems [21].

Computational fluid dynamic is an effective method to study the RERDs. In recent years, simulations about the RERD have been successfully conducted by some authors for improving the performance of the device. Z. Yihui [22] developed a 2D numerical simulation for the RERD to simulate the dynamic mixing process in the ducts. L. Yu [23] designed a 3D simulation model of the RERD to investigate the mixing progress and the relationship between the fluid mixing, flow rate and rotation speed. In the previous work of our research group, E. Xu [3, 24] developed a 3D numerical simulation for RERD, and established a theoretical formula between the inflow length and operational conditions on the basis of the mass balance and computational fluid dynamics analysis. Also, in order to form a fluid film lubrication environment for the rotating of the rotor, a hydrostatic bearing structure was first introduced and researched in the RERD, and this special structure can decrease the frictional force between the rotor and endcover, and prolong the service life of the RERD.

The objective of this paper is to employ pre-pressurization/depressurization grooves on the RERD and evaluate their effects on the flow and pressure fluctuations through 3D numerical simulations and validating experiments.

2. Experiments

The experiments were conducted using a self-made RERD in the seawater reverse osmosis (SWRO) desalination system established in our laboratory. A process flow diagram of the SWRO desalination system is provided in Fig. 2. In the figure, the seawater is in the tank1, positioned downstream of which is the feed pump, which provides the upstream minimum pressure required for the operation of the following pumps. The filter is installed after the feed pump to guarantee the quality of seawater to the RO membrane modules.

The RO membranes are fed by a booster pump and a high pressure pump. Then, the RO membranes divide the flow into two parts, one (as the permeate) is back to the tank1, and the other (as the high pressure brine) is conveyed through the RERD to recover energy and then to the tank1. The RERD is fed by the same feed pump as the high pressure pump. The flow rate and the pressure of the streams entering and discharging the RERD are measured by the corresponding transducers preset in the pipes with a precision of $\pm 0.1\%$.

For the RERD, the rotor is driven by a servomotor, whose speed could be controlled independently. The rotor and the endcover with the pre-pressurization/depressurization grooves adopted are shown in Fig. 3.