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Performance prediction of hydraulic energy recovery (HER) device with novel mechanics for small-scale SWRO desalination system

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ABSTRACT

The biggest proportion of the cost of desalted water is the energy consumption, especially for small-scale SWRO desalination system. In order to decrease the cost of desalted water, the energy recovery device is preferred to be considered in small-scale SWRO desalination system. However, the investigation of energy recovery device for small-scale SWRO system is scarce. Until now the design of energy recovery device has not been based on the results of the mathematical simulation but almost on experimental and empirical knowledge, and there are few detailed reports about the optimal design of energy recovery device for small-scale SWRO desalination system in previous articles. In the current paper, a hydraulic energy recovery (HER) device with novel mechanics is introduced, the detailed simulation results of the HER device and specific energy consumption of small-scale SWRO system equipped with the HER device are presented. The simulated results are very useful for optimal design of the HER device and its coupling SWRO desalination system.

1. Introduction

The biggest proportion of the cost of desalted water is the energy consumption, contributing almost 50% of the total desalted water cost, especially for small-scale SWRO desalination system [1]. Global energy crisis and the increasing demand for more fresh water are pushing the SWRO desalination industry to use renewable energy and improve the operational efficiency of the SWRO desalination system. In one hand, wind-powered and solar-powered SWRO systems have been studied [2–5]. However, the applications of the renewable energy for desalination are restricted by geographical and climatic conditions. On the other hand, the operational efficiency of the SWRO system is affected by equipments, reverse osmosis membrane, and hydraulic energy recovery device especially. Existing energy recovery devices, such as DWEER [6], SalTec DT [7], PX [8] and hydraulic TurboCharger [9], have been mainly applied to middle/large-scale SWRO plants, and have lowered the specific energy consumption to 2.33 kW h/m^3 [10], but few of them is suitable in small-scale SWRO desalination system. So, conventional small-scale SWRO desalination systems usually aren't equipped with energy recovery device. A throttling valve was utilized to provide the operating condition of high pressure in small systems. Typically, 70% of the input power is wasted in the valve, consequently, such systems often consume more than 10 kW h/m^3 product water [4]. In order to decrease the cost of product water for such system, a practical energy recovery device is preferred to be considered. However, the investigation of energy recovery device for small-scale SWRO system is scarce. Until now the design of energy recovery device has not been based on the results of the mathematical simulation but almost on experimental and empirical knowledge, and there are few detailed reports about the optimal design of energy recovery device for a small-scale SWRO desalination system in previous articles.

In the current paper, a hydraulic energy recovery (HER) device with novel mechanics is introduced, the detailed simulation results of the HER device and the specific energy consumption of small-scale SWRO system equipped with the device are presented.

2. HER device

2.1. Basic mechanics of HER device

The HER device recovers the hydraulic energy from the high pressure brine steam and returns it directly to the feed seawater. The basic mechanic of HER device is shown in Fig. 1a. The two pistons are connected by a central rod and are assembled in two cylinders, respectively. The middle locator of the two cylinders is the directional valve nest, which achieves the switch of flow direction of high pressure brine and discharge brine. The four check valves are installed at the end of the cylinders. In Fig. 1b the feed and the high pressure brine both act to push the pistons to move, thus driving the pressured seawater. When one piston reaches to the front of the directional

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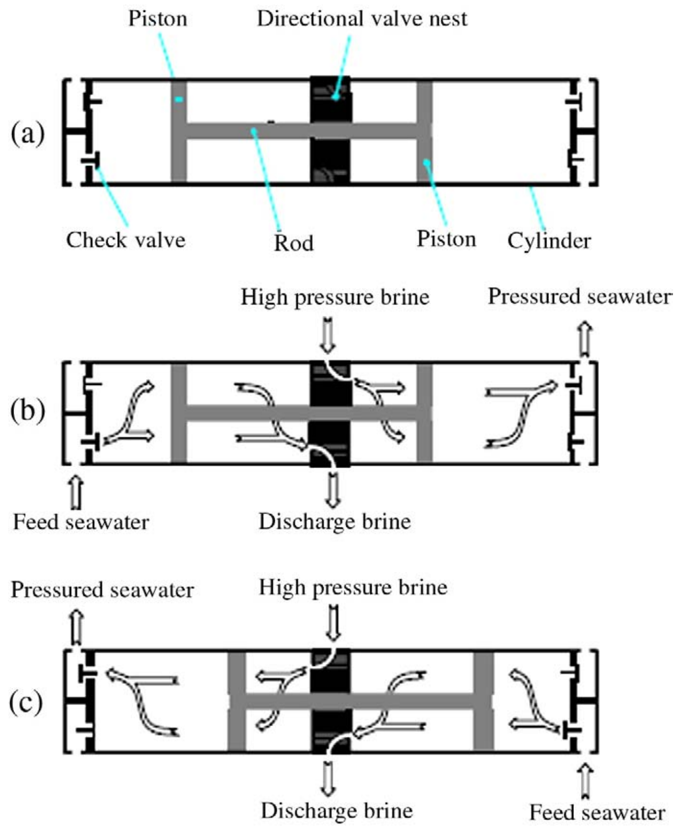

Fig. 1. Basic mechanics of HER device.

valve nest, it pushes the directional valves to the next station, after that the moving direction of the pistons are reversed, as shown in Fig. 1c, and the piston travels back to the left, until it again reverses.

2.1.1. Directional valve nest

Within the directional valve nest the two important flows are the flow in from the membrane modules and flow out to the discharge pipeline. During the steady-state moving of pistons in cylinders, the flows are constant. However, during switching process of directional valves, the flows are varied with the different localities of the directional valve.

Directional valves' timing is critical to minimize pressure surges and avoid the water hammer causing by the change of flows in the cylinders. For this reason, four check valves are used and accumulators should be installed in SWRO system. Unlike the Clark pump[4] and the Pressure exchanger–intensifier[11], directional valves of HER device are installed inside and are driven by the pistons. Since the switches of the directional valves belong to an instantaneous process, the pressure surges during the switches can be effectively weakened or even eliminated.

2.2. Mathematical model of HER device

According to previous articles [4,11], leakage is very small in the cylinders, on the assumption that the leakage is very small in the cylinders. Here, leakage is assumed negligible. When applying the force balance to the HER device's pistons, the equation can be expressed as:

$$(P_{HB}-P_{DB})A_0 + (P_{FS}-P_{HS})A_1 = F_f \tag{1}$$

where

$$A_1 = \frac{\pi}{4}D^2 \tag{2}$$

$$A_0 = \frac{\pi}{4}(D^2-d^2) \tag{3}$$

$$R = \frac{d^2}{D^2} \tag{4}$$

$$\frac{A_0}{A_1} = 1-\frac{d^2}{D^2} = 1-R \tag{5}$$

$$F_f = k(P_{FS}A_1 + P_{HB}A_0). \tag{6}$$

Combining Eqs. (2)–(6) with Eq. (1), the feed pressure can be expressed as follows:

$$P_{FS} = \frac{P_{HS} + P_{DB}(1-R)}{1-k} - P_{HB}(1-R) \tag{7}$$

and the flows obey:

$$Q_{FS} = Q_{HS} = \frac{Q_{HB}}{1-R} = \frac{Q_{DB}}{1-R}. \tag{8}$$

2.3. Efficiency

2.3.1. HER device efficiency

If HER device is represented as a black box, the energy inputs and outputs could be illustrated as in Fig. 2. The energy balance of HER device is calculated by the following formula:

$$E_{out} = E_{in} - E_{waste}. \tag{9}$$

The HER device efficiency is defined as follows:

$$\eta_{HER} = \frac{E_{out}}{E_{in}} \times 100\% = \left(1-\frac{E_{waste}}{E_{in}}\right) \times 100\% = \frac{Q_{HS}P_{HS} + Q_{DB}P_{DB}}{Q_{FS}P_{FS} + Q_{HB}P_{HB}} \times 100\%. \tag{10}$$

2.3.2. Pressure transfer efficiency

Pressure transfer efficiency is an important guideline for HER device, which can be calculated by the following equation [12]:

$$\eta_p = \frac{Q_{HS}P_{HS} - Q_{FS}P_{FS}}{Q_{HB}P_{HB} - Q_{DB}P_{DB}} \times 100\%. \tag{11}$$

2.4. Specific energy consumption

Specific energy consumption is calculated by dividing actual electrical power input to the high pressure device and the low pressure feed device with product water, which is expressed in kWh/m^3.

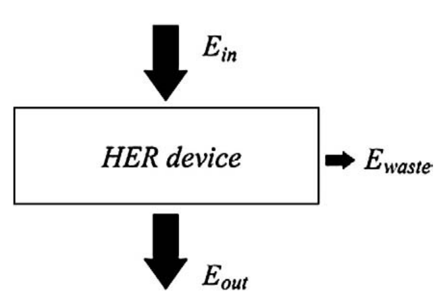

Fig. 2. Energy flow of HER device.