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Review of performance improvement of energy recovery turbines in the reverse osmosis desalination

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ABSTRACT

In reverse osmosis desalination industry, the reduction of energy consumption is always one of the hottest topics. In some cases the energy recovery technology can reduce the energy consumption of the reverse osmosis desalination system by 40%–50% [1]. There are mainly four kinds of energy recovery devices: Pelton wheel, reverse running pump, hydraulic turbo charger and pressure exchanger. Hydraulic turbo chargers, one main kind of energy recovery devices, have good applications in reverse osmosis desalination projects because of low initial cost, easy installation and maintenance, availability for a wide range of heads and flows, small footprint, low noise and acceptable efficiency. Moreover, it can be used as a pressure booster for the treatment process of the inter-stage pressurized wastewater reverse osmosis. Its best transfer efficiency reported is 82% [2]. With the popularizing of hydraulic turbo chargers, how to increase the efficiency of turbo chargers causes more and more attention. This paper reviewed kinds of methods to improve the efficiency and performance of hydraulic turbines in desalination industries. Based on computational fluid dynamics simulation and analysis, optimizing the design of the impeller and blade geometry to reduce the impact loss is one of the useful ways to increase the efficiency. Coating the wet surface of turbine plays an important role in improving the wear resistance in surfaces and extending the life of components. To improve the efficiency of turbine at part load, adjustable inlet guide vanes were studied and its inlet angle and outlet angle were optimized. Based on the previous research results and its limitation, future study for improvement and implementation of hydraulic turbine were also discussed.

Keywords: Reverse osmosis desalination; Energy recovery turbo charger; Efficiency improvement

1. Introduction

How to reduce the cost of reverse osmosis (RO) desalination has always been a hot topic in recent years. The cost of energy in seawater reverse osmosis (SWRO) process is usually about 30%–50% of the total production cost of water and can be as much as 75% of the operating cost, depending on the cost of electricity [3]. With the help of energy recovery devices (ERD), the energy consumption of SWRO desalination has been reduced a lot. But there is still potential to improve the efficiency, stability and capacity of these ERD.

It was reported that the commercial major ERD included the impulse turbine (Pelton wheel), hydraulic turbo charger, work exchanger, pressure exchanger and reverse running pump (Francis turbine) [2]. Reverse running pump is mainly used in old systems but not popular now because its hydraulic to shaft power efficiency (maximum 75%) is lower than others. Pelton wheel's hydraulic to shaft power efficiency is in middle range (80%–90%) and the units are relatively inexpensive. A common characteristic of the Pelton wheel and the Francis turbine is that these transfer the energy recovered from brine back to the high pressure pump (HPP) via the shaft. While computing the transfer efficiency, the energy lost

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by the HPP and the reduction in the wheel's energy efficiency must also be taken into account [4]. But the Pelton turbines do not reduce the size of the HPP. Moreover, if the unit is not properly positioned and designed in an RO plant, the system could suffer from loss of efficiency [5]. The two exchangers, with best transfer efficiency (ratio of total energy output to the total energy input to the unit expressed as percentage) of 91%–96%, suffer from high level of complexity, problem of brine and feed mixing and high capital cost. The turbo charger is specifically designed for RO desalination systems and very simple. Though the energy transfer efficiency of turbo charger is not high compared with the two exchangers, the turbo charger has the lowest capital and installation cost, and its Life Cycle Cost is also good.

Currently, the technology of hydraulic turbo charger is very mature. The efficiency seems to be the most important factor and the design of turbines mainly aims to obtain the best efficiency. For hydraulic turbo charger in desalination system, the peak transfer efficiency can reach 82% now, but there is still some room for further improvement, especially when the flow rate changes. This paper reviewed the technology development of turbo chargers in RO desalination which can improve the efficiency in recent years.

2. Optimization design

2.1. Blade

With accumulated experimental and numerical data and computational fluid dynamics (CFD) technology, optimizing the hydraulic performance becomes more and more easy and reliable. The blade profiles refining can increase much more efficiency than other components modification. In some cases, more twisted blade in 3D space, such as X-type for Francis turbines, can improve the efficiency over 5% [6]. With the help of aerodynamic turbo optimization method and turbine design theory, the impellers are specially designed for turbine applications, so the best efficiency of turbo can be increased 13% compared with the efficiency of pump as turbine (PAT).

The radial blade type (blades inlet angle of 90° or approximate to 90°) hydraulic turbine has attracted the attention of users and researchers. Testing and application show that its efficiency is increased by 5% compared with the PAT, in the same conditions and operating conditions (flow rate: 196 m^3/h, head: 1,586 m, rotating speed: 3,570 rpm). The research of Pacific Pump Ltd. shows that radial blade hydraulic turbines have the following advantages over PATs: (1) high energy conversion efficiency; (2) same efficiency may be achieved with fewer stages, which offers simpler structure and higher reliability; (3) smaller impeller diameter, compacted structure and the lower cost and (4) the nozzle can be adjusted easily, so it can expand the scope of the flow rate [7].

2.2. Replaceable volute, diffuser ring and nozzle ring

Pressures can vary significantly because of changes in salinity, temperature and performance of membrane over the life of a plant. This makes the turbocharger work off its best efficiency point and can result in an efficiency loss of approximately 2%–5% and perhaps more in some cases. To cope with these changes, we can use replaceable volute, pump diffuser ring and turbine nozzle ring [2]. The volute inserts are radially split mirror image halves that allow the complete machining and surface finishing of the volute's waterway. On one hand, this design makes the turbine manufacturing more flexible, which means that every turbine can be designed and manufactured according to every working condition, so the efficiency can be guaranteed. On the other hand, it allows for an economical replacement of these parts to accommodate new operation condition. By using these replaceable parts, people can store several sets of these low-cost volute inserts, diffuser rings and nozzle rings so that when operating conditions change, the equipment efficiency is restored with minimal downtime and cost.

2.3. Bearing lubrication

Membranes, headers and associated piping partially drain during shutdown and this could result in momentary operation with a dry thrust bearing during start-up. The patent-pending design called ROTOR-FLO™ uses feed water as the lubricant to provide optimal lubrication to the rotor thrust bearing (Fig. 1). This design ensures full lubrication at the instant of start-up. And the radial flow channels can automatically increases bearing pressure as rotor speed increases.

2.4. Guide vane

In the operation of the turbine, when the flow rate changes, the efficiency of the turbine will change accordingly. And while the flow rate is reduced to 40% of the optimal efficiency point, the turbine may not recover the energy [8]. One of the most applicable methods to solve this problem is to add adjustable inlet guide vanes (IGVs) (Fig. 2).

Guide vanes are key hydraulic components in large centrifugal air compressor, pump and hydraulic turbine to guide the medium flow and reduce hydraulic loss. While IGVs which set between turbine flume and impeller have the same aforementioned function by being used to change the inflow angle of medium in hydroturbine or PAT, sequentially more hydrodynamic power can be generated when working medium impact the impeller. The rate of flow and pressure can be controlled by adjusting the opening of IGVs to accommodate requirements of different working conditions and improve the performance (Fig. 3).

Sulzer Pump Ltd. has begun to develop a PAT with IGV, and gives the performance curves of the regulation.

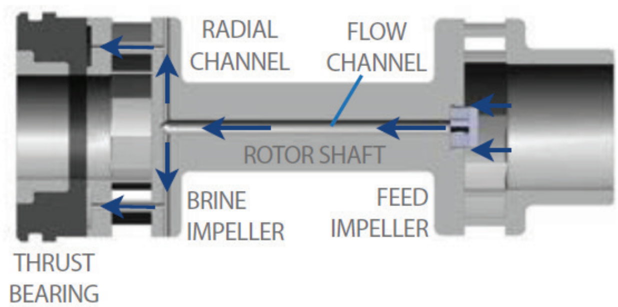

Fig. 1. Lubrication channels.

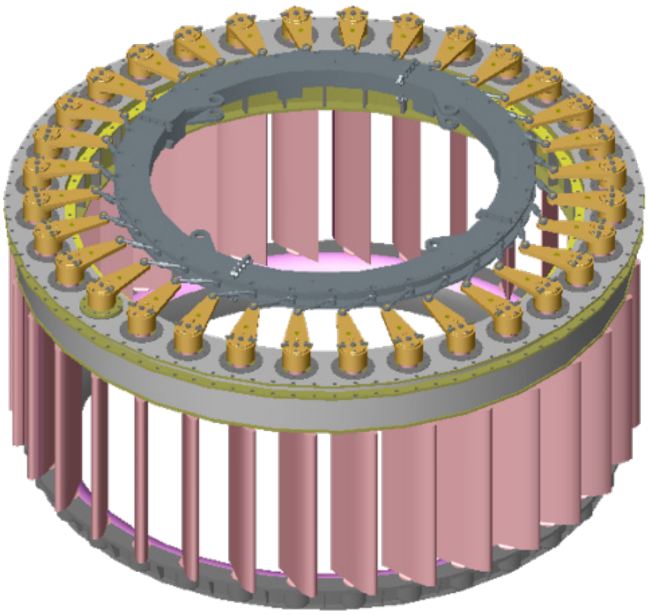

Fig. 2. IGV of hydroturbine.

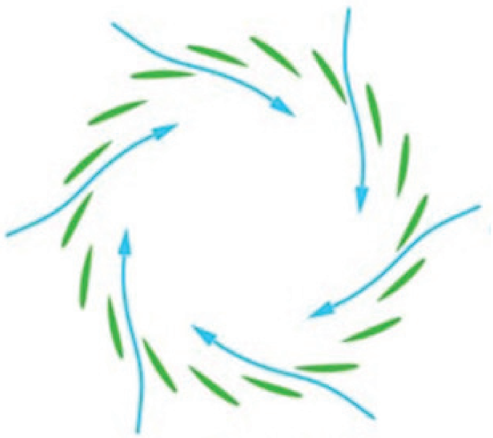

Fig. 3. Condition of the flow via the IGV.

Experiment has proven that, when the turbo operating conditions deviate from the best efficiency point, the efficiency change can be limited within 7%.

In a single-volute pump design, uniform or near uniform pressures act on the impeller when the pump operates at the design capacity. At other capacities, the pressures around the impeller are not uniform and there is a resultant radial reaction [9]. High side loads result in higher bearing loads, shorter bearing life and reduced efficiency. However, adding multivane diffuser between the impeller and volute can significantly reduce radial imbalance force of turbo shaft to get the maximum efficiency and extend the radial sliding bearings life.

3. Hydraulic energy management integration

A system called hydraulic energy management integration (HEMI) has been used in SWRO desalination plants

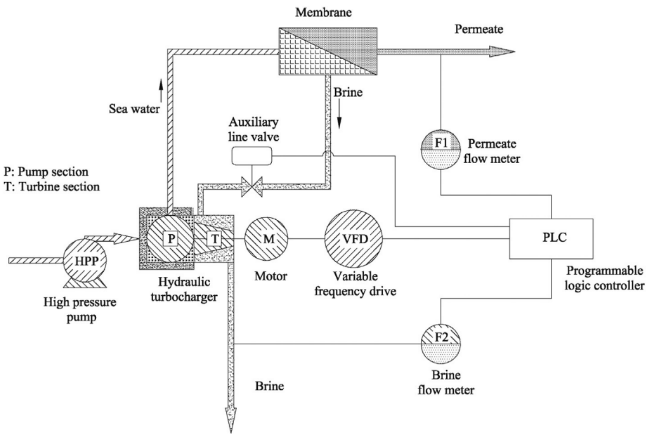

Fig. 4. Control scheme of the HEMI system [12].

(Fig. 4). The rotor of the turbo charger is connected to a motor equipped with a variable frequency drive (VFD). The HPP works at constant speed, constant flow and delivers constant feed pressure. The HEMI system recoveries the energy of brine and raises the feed pressure to desired membrane pressure. If the feed pressure of turbo charger cannot meet the requirement of RO system, the motor and VFD are engaged to increase the turbo speed and feed pressure [10]. The HEMI can dispense with feed water pressure control valves (elimination of throttling loss) and VFD on HPP, hence reduces the energy consumption and capital cost [11]. Oklejas et al. [12] studied the cost of permeate (feed flow rate: 950 m^3/h, recovery: 40%) and found that the HEMI displayed about a 2% lower specific energy consumption than a standard HPP with VFD and turbocharger. Recent advances in turbocharger design have greatly expanded the hydraulic range by using 'variable geometry' turbine nozzles. These nozzles can be adjusted to vary the flow area as required to accommodate varying membrane operating requirements.

4. Surface improvement

Reducing the roughness of turbine interior surfaces (i.e., volute and rotor) can improve the efficiency by minimizing frictional loss. There are some methods such as grinding, coating and painting are used to achieve surface improvements. For example, coating the surface with silicone-based fouling release system can improve surface roughness and limit organic growth [13]. Coating of stationary and rotating seal rings, guide vanes and inlet and outlet edges of the runner can keep turbine in good performance. In some cases, field tests found that efficiency may improve 0.1%–0.8% comparing pre-coated vs. post-coated performance [6].

5. Computer aided design (CAD) and CFD

The turbo charger is basically an integral turbine driven centrifugal pump. The goal of the design process is to match the turbine power output with the pump impeller power absorption, with both occurring at the same speed and at their respective best efficiency points [2]. With the help of advanced computer technology, the impeller geometry, multivane diffusers, turbine volutes and nozzle rings can be customized, then the hydraulic performance can be analyzed to see if it meets the requirements. Hence, every turbine can work at the highest efficiency at the customer's unique operating conditions. Of course, the design requires an accumulated database of experiments and years of experience.

Many researchers have done lots of research on CFD analysis, for example, improving pressure recovery in draft tube, cavitation research, tip clearance, prediction of erosion and performance in off-design condition. The CFD technology not only increases energy conversion efficiency by optimized shape of turbine runners and guide vanes, but also decreases cavitation damages in high head plants and abrasion effects when dealing with heavy sediment-loaded propulsion water [6].

6. Conclusions

This paper reviewed lots of methods to improve the efficiency of hydraulic turbo charger such as radial blade, modifying the blade tip shape, replaceable volute, diffuser rings and nozzle rings, grinding and coating surface and so on. Currently, the peak efficiency of hydraulic turbo charger almost reaches the theoretical limit. But practically, the energy recovery turbo often runs in off-design conditions because the temperature and salinity of seawater and the performance of RO membrane are always changing. Therefore, improving the off-design efficiency is also important. It has been proven by analysis and experiment that IGV and HEMI can effectively broaden the performance curve and improve the efficiency of turbines.

Modern CFD flow analysis has been a powerful tool in hydraulic turbine field, and significantly improved turbine efficiency, production accuracy and shortened the period of R&D. But it is not good enough now. In the future, CFD method needs to improve the off-design operation simulation accuracy.

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