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Current status and future directions of MED-TVC desalination technology

Ibrahim S. Al-Mutaz*, Irfan Wazeer

Chemical Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
Email: almutaz@ksu.edu.sa

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ABSTRACT

Desalination has now become one of the major water treatment processes in several countries around the world where shortage of water is a serious problem. Energy consumption is a vital economic factor in selecting the type of desalination processes because current desalination processes require large amount of energy which is costly. Multi-effect desalination system with thermal vapor compression (MED-TVC) is particularly more attractive than other thermal desalination systems due to its low energy consumption. MED-TVC is characterized by high performance ratio, easier operation, low maintenance requirements and simple geometry. These attractive features make MED-TVC highly competitive to other well-established desalination techniques that include the reverse osmosis and multi-stage flash desalination. The primary goal of this paper is to present a preview of some aspects related with the theory of the technology, parametric study of the MED-TVC systems and its development. It will analyze the current and future aspects of the MED-TVC technology in view of latest installed plants.

Keywords: Multieffect evaporation; MED-TVC; Desalination development; Thermal desalination

1. Introduction

The demand for high-quality water greatly increased during the last several decades due to rapid growth in population accompanied by the increase in standard of living, together with the expansion of industrial and agricultural activities [1–3]. Although, the world is almost covered with 97% of seawater but it is a fact that the seawater is unsuitable for human consumption and for industrial and agricultural uses [4]. Therefore, the increasing demand of fresh water becomes the main reason for applying different desalination technologies to produce purified water for the utilities [5,6]. Currently, several countries especially Gulf cooperation council countries (GCC) are using desalination techniques to prepare potable and industrial water for their requirements [7,8]. For instance, Saudi Arabia, United Arab Emirates (UAE) and Kuwait are using desalination techniques on large scale for purified water [9].

Total installed desalination capacity in the world is around 66.4 million m^3/d at present [10]. The expected installed capacity is estimated to reach 98 million m^3/d by 2015 [11]. Most of the existing desalination plants use thermal (multi-stage flashing (MSF) and multi-effect desalination (MED)) and membrane desalination processes (reverse osmosis (RO)) [12–20]. The percentage desalination technologies worldwide and in GCC countries are shown in Fig. 1 [21]. The current

*Corresponding author.

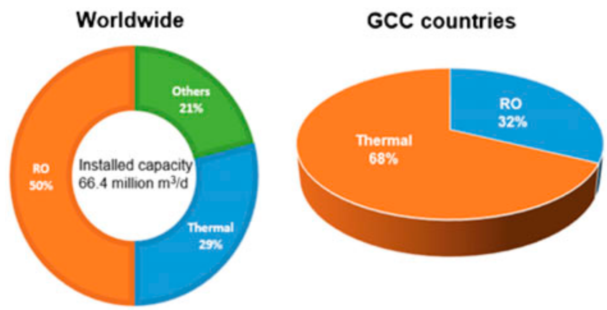

Fig. 1. Installed desalination capacities worldwide and in GCC countries by process (2011) [21].

worldwide desalination market share is about 50% for RO process while 29% for thermal technologies. However, in GCC countries, thermal process represents 70% market share [22]. Normally, thermal processes are preferred over RO in GCC countries due to water and environmental conditions, e.g. high seawater salinity and temperatures [23].

2. MED-TVC plants: state of art

MED system is more energy efficient than other desalination processes like MSF because it reduces the energy consumption required to heat water [24–27]. During the 60s and 70s, most of the desalination plants installed in the Middle East were MSF kind. Since MSF has huge capacity with less efficiency, thermal vapor compression (TVC) addition results in a competitive and energy-efficient MED. MED process has attracted research interest recently because of large volume MED development having over 15 MIGD (million imperial gallon per day). Additionally ending life of MSF in the Middle East is increasing MED demand [28].

Among different types of MED system, the most attractive MED configuration has been horizontal tubes falling-film evaporation (HT–FF–MED) with TVC [29]. The HT–FF–MED with TVC has become an attractive choice for Middle East region because of such factors as ease of operation with any heat source available, low scale formation, and high performance ratio (PR) [30]. Demineralized or potable water production can be best carried out using MED system provided the availability of low-cost energy source [31]. MED system demands comparatively lesser energy in terms of heating steam and/or electrical energy than the other conventional desalination systems such as MSF and RO. Currently waste heat energy, taken from thermal or gas turbine power plants, based on many MED systems is in operation in the Middle East region. For example, Iran's Kish Island heat recovery steam generator (HRSG) provides heating steam supply to MED-TVC systems of 2,000 m^3/d [29].

SIDEM/ENTROPIE is the world-leading company in low temperature desalination processes using seawater. Different MED plants have been installed since 1980 and mainly the French company SIDEM has been involved in commissioning these systems [32]. Recently SIDEM has developed, in particular, in the UAE, TVC system in different projects worldwide. Das Island in UAE received the maiden two MED-TVC units, based on two effects, with unit capacity of 125 m^3/d in 1973. Later in 1979, the unit capacity increased to 1,500 m^3/d after installing four units in Ruwais Refinery [33]. Jabal Dhana and Sila along with Mirfa were among those remote areas of UAE where very first MED-TVC desalination units were commissioned in December 1991. One unit was installed at Jabal and Dhana having 1 MIGD capacity with four effects and GOR of 8 while two units having capacity of 1 MIGD with four effects and 8 GOR were installed at Mirfa. For the supply of 25 bar motive steam, a boiler was used as well [34]. In 1995 Sicily (Italy) received the next unit of 2 MIGD capacity comprising four identical units; each with 12 effects and gain ratio of 16 while taking 45 bar steam from two boiler units [35]. The satisfactory plant performance increased desalination units demand and SIDEM commissioned more units of 1, 1.5, and 2 MIGD from 1996 to 1999 in UAE followed by two units, each of 3.5 MIGD, in 2000 in Umm Al-Nar and 14 units of 3.77 MIGD in 2002 in Al-Taweelah A1. Each unit comprised nine effects and GOR close to 8 while 2.8 bar steam was supplied to steam ejectors via steam turbine [36]. In Layyah, the next desalination unit was installed having 5 MIGD capacity using medium pressure motive steam [33]. In May 2007, Western Australia received two TCD (thermo-compression distillation) mode-based thermal desalination plants; each producing 3,600 m^3/d of high-purity water.

One of the largest MED-TVC plants having total capacity of 176 MIGD is built in Al-Jubail industrial city [37]. Currently, Yanbu Phase 2 Expansion MED seawater desalination plant in Saudi Arabia is the world's largest MED unit desalination plant. Entropie received three more contracts in 2013. First supply of a desalination plant having 5,362 m^3/d capacity has been offered to China Machinery Engineering Corporation to be installed in Venezuela. Secondly, Daewoo E&C (Korea) demanded desalination unit with total capacity of 5,000 m^3/d to be supplied at Zwitina power plant in Libya. Finally, Posco Engineering and Construction Co. Ltd, awarded contract for 5,000 m^3/d

desalination plant the supply for the Cochrane Thermoelectric Power Plant in Chile. Several projects of MED-TVC with different capacities commissioned by SIDEM are listed in Table 1 [38].

3. Process description

A schematic diagram of a MED-TVC system with n effects is shown in Fig. 2. The main components of the system are the condenser, steam jet ejector which acts as a thermal compressor, and falling film evaporators which are also known as effects.

Motive steam S from the external source such as boiler or power plant is introduced into the steam jet ejector at relatively high pressure P_s. Steam jet ejector is used to enhance the efficiency of the system. Motive steam is used to compress portion of the vapor formed in the last effect by using the principle of gas dynamics. The compressed vapor along with expanded motive steam $(S + D_n)$ from the ejector is entrained into the first effect as the heat source where it condenses and releases its latent heat inside the tubes. Pre-heated feed seawater is sprayed into each evaporation effect and flows down as a liquid film. The film warms up to boiling temperature due to the condensation of motive steam inside the tubes and portion of it evaporates. Part of the condensate returns to its source and other part joins the desalinated water product.

The generated vapor D_1 in the first effect is directed to the second effect. Before going into the second effects, vapor passes through the wire mesh demister for the separation of entrained brine droplets. The generated vapor D_1 acts as a heat source in the next effect at a lower pressure and temperature. The hot brine leaving the first effect, flows into the second effect, operates at a lower temperature and pressure. The vapor D_2 is generated in the second effect by flashing brine B_1 and evaporation of feed seawater F_2. This iterative process is repeated through all effects.

To enhance system PR, a portion of formed vapor in the last effect is entrained by the steam jet ejector while the remaining part is condensed in the condenser which warms up the seawater from the intake temperature T_c to a higher temperature T_f. Cooling water is used to remove the excess heat added to the system in the first effect by the hot motive steam. Non-condensable gases (NCG) that are accumulated in the condenser are vented continuously with the help of the ejector. NCG can cause production problems for system's operation and performance. They can reduce heat transfer efficiencies as well as partial pressure of the condensed vapors.

4. Effect of design parameters on MED-TVC units

Several studies [39–51] have been published to study the effect of design parameters on system performance for MED-TVC plants. Darwish and El-Dessouky [39] compared the TVC desalination process with MSF desalination system. They presented an analysis that compared top brine temperatures, gain output ratio, PR, and specific heat transfer area for MED, MED-TVC, and MSF systems. They also performed a thermal analysis of the MED-TVC system with an example. Their analysis showed that conventional MED systems are more efficient than the MSF systems because when both are equipped with steam which comes from steam turbines, conventional MED system can yield desalted water at a lower cost than the predominant MSF system. Al-Juwayhel et al. [12] performed a comparison for four different types of single-effect desalination systems. All of the four systems were combined with vapor compression heat pumps including thermal (TVC), mechanical (MVC), absorption (ABVC), and adsorption (ADVC). They

Table 1
Several projects of MED-TVC commissioned by SIDEM

Year	Country	Location	Unit capacity	Total output (m^3/d)	No. of units	GOR
1991	UAE	Mirfa	1 MIGD	9,100	2	8
1995	Italy	Trapani	2 MIGD	18,000	4	16
1997	Netherland	Curaçao island	2.6 MIGD	12,000	1	13.4
2000	UAE	Umm Al-Nar	3.5 MIGD	32,000	2	8
2001	UAE	Layyah	5 MIGD	45,696	2	8.4
2005	UAE	Sharjah	8 MIGD	36,368	1	8.4
2008	Bahrain	Al-Hidd	6 MIGD	272,760	10	8.9
2009	Saudi Arabia	Al-jubail	6.5 MIGD	809,109	27	9.8
2010	UAE	Fujairah	8.5 MIGD	454,600	12	10
2011	Qatar	Ras Laffan	6.3 MIGD	294,490	10	11.1
2012	Saudi Arabia	Yanbu	15 MIGD	146,160	2	9.7

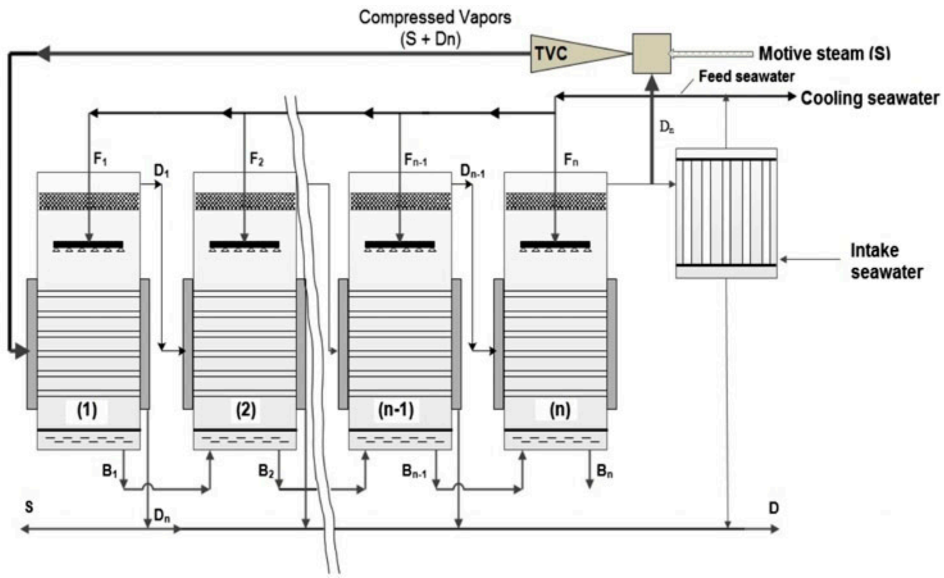

Fig. 2. Schematic of MED-TVC process with n number of evaporators.

developed mathematical models for the four systems. The model consists of energy and mass balance equations. Their model compared the PR, specific heat transfer area, specific cooling water flow rate, and specific power consumption for the four effects. Results showed that the PR of TVC system increases at higher motive steam pressures. El-Dessouky and Ettouney [30] performed an analysis for single-effect TVC systems. They developed a mathematical model for single-effect TVC desalination process, which focused on the parameters that affect the cost of the product. Their model considers the effect of various thermodynamic losses on the system PR, the specific heat transfer area, and the specific flow rate of cooling water. Furthermore, the model takes into account the effects of the fouling factors and the presence of NCG on the heat-transfer coefficients in the condenser and evaporator. Hamed et al. [40] conducted an exergy analysis to evaluate the performance of thermo-compressor, and the performance of thermo-compressor was compared against an actual desalination plant. The performance of TVC system based on exergy analysis was compared in their research against conventional MED and mechanical vapor compression (MVC) desalination systems. Their research showed that TVC system yields the least exergy destruction among the three systems. They also analyzed that most of the exergy destruction occurs in the first effect of the MED-TVC system and in the thermo-compressor. Results showed that exergy losses can be reduced by decreasing the top brine temperature and increasing the number of effects.

Al-Najem et al. [41] performed a parametric analysis, using the first and second law of thermodynamics for single- and multi-effect TVC systems. Results showed that the evaporator and the steam ejector are the major roots of exergy destruction in the TVC systems. Their study revealed that heat transfer area of each effect reduces when the top brine temperature increases, while keeping the same last effect brine temperature. On the contrary, temperature difference across each evaporator decreases due to the increase in the number of effects for the same values of top brine temperature and last effect temperature and as a result gain output ratio increases. Choi et al. [42] analyzed the thermal performance of four developed MED-TVC distillers, by a steady-state simulation program based on the first and second law of thermodynamics. These distillers had capacities of 1, 2.2, 3.5, and 4.4 MIGD. The operating conditions of the distiller are studied and verified with the PRs, distillate productions, steam consumption rates, thermo-compressor entrainment ratios, top brine temperatures and temperature differences across effects. They performed exergy analysis to identify factors for improving system efficiency. The study showed that the main source of exergy destruction in the MED-TVC systems is the TVC and the associated effects. A simulation model has been presented by Alasfour et al. [43] to examine the combination of MED and MED-TVC system in comparison with conventional MED and MED-TVC plants. They performed the parametric study on the basis of first and second laws of thermodynamics to investigate the MED-TVC integrated with a conventional MED system (MED-TVC + MED) with regenerative feed heaters in comparison with conventional MED-TVC systems with regenerative feed water heaters (MED-TVC, FH) and without them. The exergy analysis showed that the irreversibilities in the steam ejector and evaporators are the major sources of exergy destruction in all configurations. The study showed that the configuration in which MED-TVC integrated with a conventional MED system (MED-TVC + MED) is better than the other configurations because it has a lower compression ratio and it can be used for large-scale production.

Ashour [44] studied the performance of two low temperature horizontal tube MED units. He analyzed the effect of different process variables on the plant efficiency. He also developed mathematical model to optimize the plant performance.

El-Mudir et al. [45] conducted the performance evaluation of small-size TVC desalination units. In this study, some important design factors and operating conditions were reviewed and the plant operating data used to evaluate the unit performance. Ameri et al. [29] studied the effect of different parameters like temperature differences across effects, feed seawater temperature, numbers of evaporation effects and steam pressure on MED system specifications such as PR, specific heat transfer area, and cooling seawater. Results showed that there is an optimum value for number of effects in which system has best PR. This optimum value is a function of seawater salinity, effects temperature difference, and feed water temperature. The results also showed that the PR and required heat transfer area increases with the increase of inlet steam pressure while the cooling seawater flow rate decreases.

5. Development of MED-TVC

In order to improve the efficiency of MED-TVC desalination system, rapid developments have been taken place during the last 10 years [52]. The combination of conventional multi-effect unit with the MED-TVC systems is the most important development [53]. Due to this configuration, the unit capacity of the system can be increased significantly with lower brine temperature and the amount of steam to compress the large quantity of entrained vapors can also be reduced because this configuration has lower compression ratio [42]. Falling film horizontal tube evaporators (HTEs)/condensers like vertical tube evaporator and the HTE can be used in order to increase the heat transfer coefficient which lessens the required heat transfer area. Because of low temperature operation of MED-TVC systems, they are thermodynamically efficient and have low pressure drops at high volumetric vapor flows. This process is one of the most economical seawater desalination processes, because it has ability to use low-cost/low-grade heat, such as exhaust steam from power plant turbines or waste heat [34]. They systems have low-energy requirements for pumping. They work on the once through principle because they do not employ recycling. Since there is no need to recirculate large amount of brine, the power consumption is only about 2 kWh/m^3 for MED-TVC systems [54]. Historical evolution of the installed capacities of MED-TVC plants in the different countries is shown in Fig. 3.

This technology is gaining more market share especially in GCC countries. Some of the large desalination projects are listed below.

5.1. Al-Taweelah A1

Al-Taweel A1 is a power and desalination plant. It was commissioned by SIDEM in 2002 as the largest MED-TVC project in the world at that time, located in the Emirate of Abu Dhabi, UAE. It is a cogeneration plant which can produce both heat and power. It consists of 14 units; each has six effects with a total production of 3.77 MIGD and 8 gain ratio. Taweelah A10 Plant is the extension of Al-taweelah A1 and has an overall capacity of 84 MIGD.

5.2. Fujairah F2 IWPP

Fujairah F2 IWPP is a combined cycle power and desalination plant in UAE. It was commissioned in 2010 and it was the largest desalination hybrid plant in the world at that time. It is a hybrid desalination plant which combines two technologies, MED and RO. The first section of desalination plant is composed of MED system and it is the largest system of the two. It consists of 12 MED units; each has 8.5 MIGD capacity

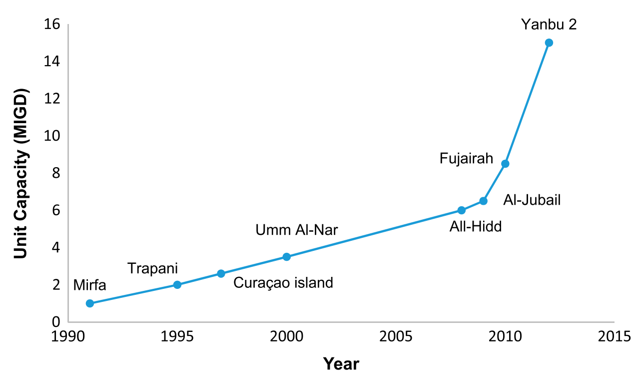

Fig. 3. The increase of unit capacity of MED-TVC systems.

and 9.4 gain output ratio. Each unit has eight effects. The first section uses steam which is extracted from the steam turbines. The second part is the RO system which is driven by power. Net water production capacity of plant is 130 MIGD [55].

5.3. Al-Jubail

Marafiq IWPP is one of the largest integrated power and desalination plant in the world. It is a combined cycle power and desalination plant with 2,750 MW power capacity and desalination output of 800,000 cubic meters per day (178 MIGD). It uses MED technology with TVC. It uses 27 MED units; each has 6.6 MIGD capacity and gain output ratio around 10. Each unit consists of eight effects. These units are driven by the steam which is extracted from gas turbines [56].

5.4. Ras Laffan

Ras Laffan C power and desalination plant also known as Ras Qartas Energy Plant is a cogeneration plant in Qatar which was commissioned on May 2011. It is the largest power and water plant in Qatar so far. It provides 2,730 MW of electricity and 63 MIGD of desalinated water. The plant consists of four steam turbines and eight gas turbines. It has 10 MED-TVC units, each having eight effects and gain output ratio of 11.1 [57].

5.5. Yanbu ll

Yanbu Phase 2 Expansion seawater desalination plant features the world's largest MED unit desalination plant. The plant was commissioned in December 2012. It has a production capacity of 15 MIGD which is more than twice the capacity of Fujairah F2 IWPP desalination plant in UAE (8.5 MIGD). Each unit consists of two effects and the total production capacity of plant is around 146,160 m per day.

6. New design and material of construction

The construction materials used in Trapani, ALBA, and Umm Al-Nar desalination plants are almost the same as shown in Table 2. These materials were selected according to SIDEM standard materials. For evaporator, condenser, and pre-heaters shells, water boxes, tube-plates, spray nozzles, and steam ejector, Stainless steel 316L was used.

Titanium was selected for the top rows of tube bundles to prevent corrosion due to the spray of water from nozzles with high velocities at the top rows of tube bundles. Aluminum brass was selected for all other tube bundles of the evaporator [53].

The latest MED-TVC units have rectangular vessel evaporators in place of circular ones, which gives much more freedom of design [58]. Moreover, 316L stainless steel is replaced by the Duplex stainless steel in desalination plants because 316L does not resist seawater containing oxygen on ppm-level Duplex has better corrosion resistance, lower weight as well as longer service life and high strength [59,60].

In 2005, the first large capacity unit of 8 MIGD was commissioned in UAE, which used the Duplex grades stainless steel. It was then used for Al-Hidd plant in Bahrain in 2006 followed by eight units in Libya in 2007, 27 units in Kingdom of Saudi Arabia in 2008, and 12 units in Peultier in 2009 [61].

7. System performance development

Several developments have been taken place to improve the performance of the MED-TVC plants during the last 10 years which can be also observed under the following points:

(1) MED-TVC process has a lot of advantages in comparison with other desalination processes. For example, it has high thermal efficiency as compared to the predominant MSF desalination process, with a lower number of effects. Moreover, it has low energy consumption and maintenance cost, simple to install, can operate at a very low top brine temperature (<70°C), and requires less pumping power.

(2) This technology is growing rapidly in large scale-desalination projects especially in GCC countries like Saudi Arabia, Qatar, and UAE. For example, world's largest MED-TVC unit of capacity 15 MIGD is in Saudi Arabia which was commissioned in 2012 [62–64].

(3) Energy consumption for MED-TVC systems is less than the other thermal desalination systems, e.g. MSF [65].

(4) By using MED-TVC systems, very high gain output ratios can be obtained. The trend of increasing gain output ratio in the past years for the large-scale desalination plants is shown in Fig. 4.

(5) Duplex stainless steels have gained in popularity in desalination plants due to many reasons. They are used as construction materials for the new desalination plants instead of 316L stainless steel because they have higher strength, low cost, and better resistance to pitting and crevice corrosion [66].

Table 2
Construction materials of the MED-TVC plants

Plant	Trapani	ALBA	Umm Al-Nar	Latest projects
Evaporator vessel	Cylindrical	Cylindrical	Cylindrical	Rectangular
Shell in contact with seawater	SS 316L	SS 316L	SS 316L	Duplex SS
Shell in contact with vapor	SS 316L	SS 316L	SS 316L	Duplex SS
Vapor and distillate boxes	SS 316L	SS 316L	SS 316L	Duplex SS
Heat tube bundles				
Tubes (top rows)	Titanium	Titanium	Titanium	Titanium
Tubes (all others)	Aluminum Brass	Aluminum Brass	Aluminum Brass	Aluminum Brass
Tube-plates	SS 316L	SS 316L	SS 316L	SS 316L
Demisters	SS 316L	SS 316	SS 31603	Polypropylene
Spray nozzles	SS 316L	SS 316L	SS 316L	SS 316L
Condenser				
Shell & tube-plates	SS 316L	SS 316L	SS 316L	Duplex SS
Tubes	Aluminum Brass	Titanium	Titanium	Titanium
Water boxes	SS 316L	SS 316L	SS 316L	SS 316L
Thermo-compressor	NA	NA	SS 316L	Duplex SS

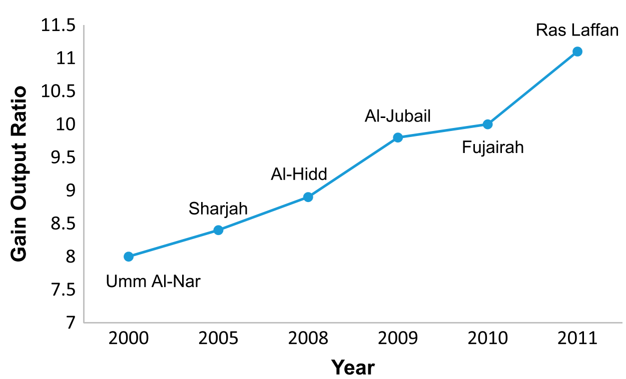

Fig. 4. The increase in gain output ratio of large-scale desalination plants.

8. Conclusion

This paper outlines different aspects of the MED-TVC technology. The new trend of combining MED-TVC with conventional MED system is one of the latest developments in this technology. One of the important features of this configuration is low compression ratio which reduces the amount of motive steam. This compact design provides an approach to increase the unit capacity of the plant.

Parametric study of the MED-TVC system by many researchers shows that the efficiency of the system depends upon design parameters such as number of effects, feed water temperature, temperature difference across the effects, etc. Maximum PR can be obtained by the optimization of these parameters. In order to minimize the cost of energy and water, most of the latest MED-TVC systems are coupled with combined cycle power plants which are characterized by high efficiency. One of the perfect examples of large hybrid desalination plants is Marafiq IWPP. It is the world's largest integrated water and power plant.

On the basis of previous experience, manufacturers have tried to enhance the performance of the new MED-TVC projects. Further development is required in order to optimize the performance of thermo-compressor in the area of design and performance. For example, efficiency of the MED-TVC unit can be affected by changing the location of thermo-compressor suction [67]. Higher efficiency in terms of energy consumption, operation, and maintenance cost and reliability should be the major goal in the designing of a desalination plant.

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