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Seven-effect 2 × 4500 m^3/d low-temperature multi-effect desalination plant. Part I: Design, installation and commissioning

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ABSTRACT

Design, installation and commissioning of Indonesia INDRAMAYU 2 × 4,500 m^3/d low-temperature multi-effect desalination plant were concerned in this paper. The process modeling, design parameters and commissioning results were emphatically stated definitely. Professional collaborative design and 3D visual design were conducted using the software of PDMS, Inventor and Promis-E. The desalination device was composed of seven-effect evaporators and a condenser with a total length of 56 m. The gain output ratio of the system was increased more than 10% than seven-effect multi-effect distillation thermal vapor compression desalination process published in former literature. Equipment installation method was also described explicitly. The debugging results show that design parameter selection for process calculation model is reasonable.

Keywords: Seven-effect desalination; Design calculation model; Thermal efficiency; Flash process; Commissioning

1. Introduction

In view of the vast sources of saline water accessible, desalination is a key component toward a sustainable water supply for the increasing global population and industrial production. It is estimated that currently there are more than 18,000 desalination plants in operation worldwide, with a maximum production capacity of around 90 million m^3 of water every day [1]. Various technologies have been used to desalinate saline water with different performance characteristics in order to improve the thermal efficiency of system [2–4]. Techniques such as the coupling of multi-effect distillation (MED) and adsorption desalination (AD), absorption heat pump and heat transfer enhancement technology give available ways of improving thermal efficiency and performance of desalination plant [5–7]. Muhammad Wakil Shahzad et al. constructed the experiments of a three-stage MED and AD (MED-AD) plant, and a series of research on the processing of MED-AD were developed. They demonstrated that the water production improvement by 2–3 folds by hybridization in a pilot comprising a three-stage MED and AD plant [8–10]. Among thermal desalination systems, MED thermal vapor compression (MED-TVC) systems with a top brine temperature (TBT) lower than 70°C have received more attention in recent years [11]. In MED-TVC system, a steam jet ejector is added to a MED system to reduce the amount of required steam (motive steam), boiler size and the amount of cooling water and, therefore, reduce pumping power consumption and pretreatment costs [12]. Zhao et al. [13] have developed steady state mathematical models to represent a MED-TVC desalination system, and parametric techniques have been used to determine the optimum operating and design conditions for the system. It is shown [14] that gain output ratio (GOR) of desalination system is much higher when TVC is used in comparison with the independent MED systems.

Most of the thermodynamic analysis performed on the MED-TVC system is based on the first law of thermodynamics. Alasfour et al. [15] have been already carried out thermal analysis

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simulation research for MED system. Raach and Mitrovic [16] performed simulation of heat and mass transfer of a MED. Aly et al. [17] developed a dynamic model for a multi-effect process which provided a reference for other dynamic models, such as the six-effect evaporator model of paper industry developed by Kumar et al. [18]. Alberto de la Calle et al. [19] described a model to simulate the thermal transient behavior of the first cell of a solar-assisted MED plant. Qi et al. [20] designed a 30-t/d low-temperature multi-effect evaporation seawater desalination (LT-MED) system based on the mathematical model and analyzed the performance of the system.

Through above analysis, the existing researches were mainly emphasized on energy-saving method of desalination. Most studies do not involve the clear design principles and methods of a desalination plant from the process calculation, equipment design to installation and commissioning. The preceding studies were mainly focused on the simulation of MED-TVC or MED-AD (including modeling, heat and mass transfer, etc.) and pilot scale device performance. However, with the rapid deterioration of water resource, the MED desalination device has been developing toward large-scale. Meanwhile increased production capacity is helpful to reduce investment and operation cost for each ton of fresh water. This paper focuses on the specific development process of 2 × 4,500 m^3/d MED desalination technology in Indonesia INDRAMAYU. The design conditions, brief process description, modeling, 3D visual design, installation and commissioning results were discussed emphatically, which will provide a very good model and reference for engineering practice of large and medium-sized desalination plant. The 2 × 4,500 m^3/d MED desalination device is designed by the institute of seawater desalination and multi-purpose utilization, SOA (Tianjin), which is the first export of the largest independent technology desalination plant from China.

2. Design parameters and requirements

The design and implementation of the desalination process should consider synthetically the factors of heat source quality, raw water quality, gained output ratio, electricity consumption, capital costs and local water demands [21, 22]. The design requirements and desalting device-operating conditions are elaborated strictly below.

2.1. Design conditions

2.1.1. Quality of raw water sources

Raw seawater is taken from the north coast of Java Island of the power plant. Suspended solids content is 100–150 mg/L; temperature is 30°C; and the salinity varies from 33,000 to 34,000 mg/L. The detailed water quality indicators are shown in Table 1.

In order to reduce corrosion of the heat exchange tubes, the seawater feeding into the desalination evaporator should better meet the following requirements, which is shown in Table 2.

2.1.2. Motive steam

In the initial start-up phase of operation the desalination evaporators was provided with the steam of 1.4 MPa and 350°C from the auxiliary boiler. In the normally running phase the desalination evaporators was motived by the steam of 0.8~1.0 MPa and 350°C. In these two stages a branch of the motive steam was used for maintaining the running of the ejection vacuum pump.

2.2. Design requirements of the desalination device

The specific design requirements on the rated conditions are listed in Table 3. The rated conditions are presented clearly in Table 4.

3. Process design

3.1. The determination of overall design scheme

The MED process consists of a series of multi-effect evaporators (generally from 2 to 16). The internal of them are kept in the state of negative pressure in order to reduce the boiling

Table 1
Analysis of seawater quality

No.	Parameter	Unit	Water analysis	
			Location A (2 kilometres far away from the coastal)	Location B (near coastal of Java Island north of the power plant)
	Physical			
1	TDS (total dissolved solids)	mg/L	33,415	33,575
2	Temperature	°C	30	30
3	Conductivity	μs/cm	42.3	42.3
	Chemical			
4	pH	mg/L	7.97	7.90
5	Silt	mg/L	≤1.0 mm	≤1.0 mm
6	Free chlorine	mg/L	0.67	0.86
7	Petroleum-like matters	mg/L	≤1.0	≤1.0
8	COD_{Mn}	mg/L	≤5	≤5
9	H_2S		≤0.1	≤0.1
10	Free oil		≤1.0	≤1.0

Table 2
Quality requirements of seawater feed into desalination evaporator

Symbol	Value	Unit
Suspended solids	≤20	mg/L
pH	6.8~8.8	/
Silt	≤1 mm	/
Cl^-	0.5~1.0	mg/L
Petroleum-like matters	≤1.0	mg/L
COD_{Mn}	≤8	mg/L
TDS	≤50,000	mg/L
H_2S	0.1	mg/L
Free oil	1	mg/L

Table 3
The specific design requirements on the rated conditions

Item	Value	Unit
Production capacity	4,500	m^3/d
TDS	≤10	mg/L
GOR	≥10	/

Table 4
The rated design conditions

Item		Value	Unit
Motive steam	Pressure	0.8	MPa
	Temperature	350	°C
Raw seawater	Temperature	30	°C
	Salinity	33,000–34,000	mg/L

point of seawater. Usually the GOR increased with the number of effects when the design conditions are invariable, meanwhile leading to higher investment. In order to meet the design requirement of GOR and keep investment as low as possible, the determination of number of effects and nominal temperature difference is 7°C and 3.5°C, respectively. The steam from power-plant waste heat or other sources was injected into the first effect evaporator. The falling-film horizontal-tube evaporator has been adopted in the 2 × 4,500 m^3/d MED system. The secondary steam produced by the partial evaporation of seawater is transferred inside the heat exchange tubes into the next effect evaporator and used as the heat source of next effect. The spraying liquid distribution of feed seawater on the outer surface of the heat transfer tubes and the flowing status of steam inside the tubes are shown in Fig. 1.

In addition to the above-mentioned design determinations, the feeding mode of raw seawater and the flow patterns of feed liquid had also to be decided primarily based on the preliminarily design calculation. Through calculating tentatively heat balance and analyzing the factors which affected the dimension of MED device host, the grouped feeding way of raw seawater and countercurrent flow of feed liquid is used in this design. The first feeding group includes the effects of one to three. The second feeding group contains

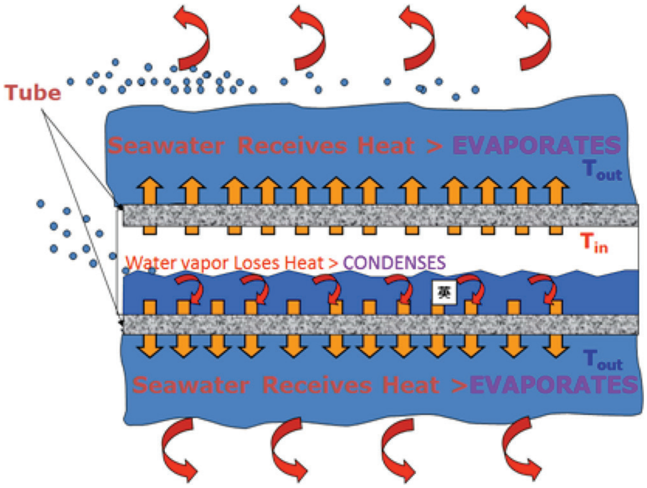

Fig. 1. Condensation of steam (inside) and evaporation of feed seawater (outside).

the effects of four to seven. The overall design scheme of the 2 × 4,500 m^3/d MED device is shown in Fig. 2.

3.2. Process calculation

The mathematical model for the technological process parameters was calculated using the self-designed software "MEDGYV2010". The specific calculation method is given as follows.

3.2.1. Calculation of input quantity of raw seawater

The input quantity of raw seawater can be calculated according to the concentration ratio and production capacity of desalination device. The demand for raw seawater of desalination evaporators can be represented as:

$$L_f = \beta G_D / (\beta - 1) \tag{1}$$

where β is the concentration ratio of desalination device, while G_D is the production capacity of desalination device.

It is important to note that the quantity of raw seawater feeding in condenser is often higher than demand of the evaporators in order to make the secondary steam cooled and condensed completely produced by the last effect evaporator (i.e., the seventh effect). This is because the temperature of seawater feeding into condenser is normally higher than 20°C, even more than 30°C in summer. Therefore, the total raw seawater demand of MED host should be determined as the expression:

$$L'_f = G_{D7}\gamma_7 / [c(t_o - t_f)] \tag{2}$$

where L'_f is the total raw seawater demand of MED host. G_{D7} is the amount of the secondary steam produced by the last effect evaporator. γ_7 is latent heat of the secondary steam produced by the last effect evaporator. c is the specific heat capacity of seawater feeding into condenser. t_o and t_f are the outlet and inlet temperature of the liquid feeding into the condenser, respectively.

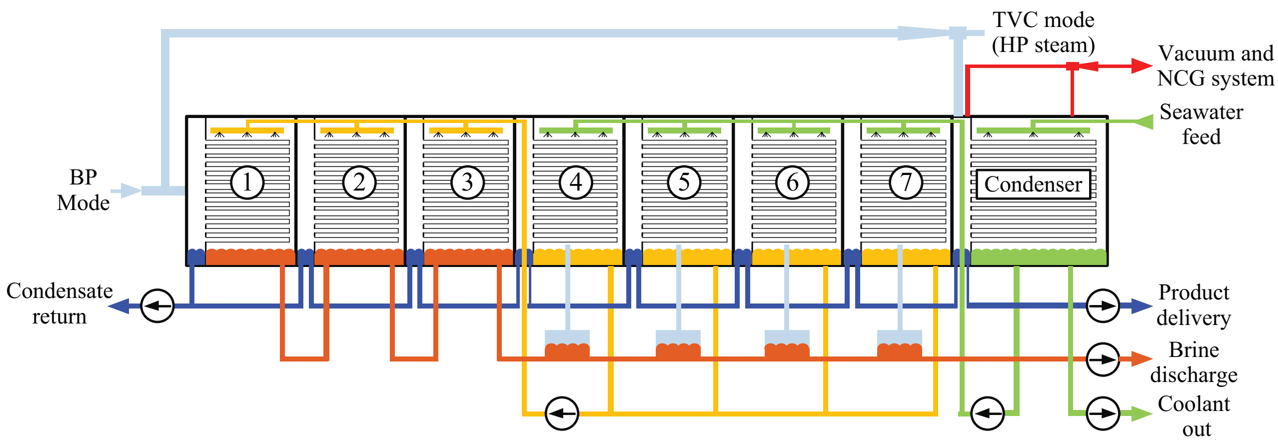

Fig. 2. The overall design scheme of the 2 × 4,500 m³/d MED device.

After outflowing from the condenser of the seawater, one part will be fed into evaporators as the feed liquid. The other part will be discharged into the sea as the cooling water. The quantity discharged into the sea can be expressed as:

$$L_c = L_f' - L_f = L_f' - \beta G_D / (\beta - 1) \quad (3)$$

where L_c is the amount of raw seawater discharged into the sea as the cooling water.

Besides the mentioned basic requirements for seawater, a small amount of raw seawater would also be consumed in order to keep the steam jet vacuum pump running smoothly. Hence the total intake of seawater can be presented as:

$$L_{tf} = L_f' + L_{vp} \quad (4)$$

where L_{vp} is the amount of raw seawater consumed by steam jet vacuum pump.

It can be seen from the above analysis that the total intake of raw seawater changes with its temperature varied greatly during different seasons. Therefore, it is best to equip variable frequency regulation for all of water pumps used in the desalination device.

3.2.2. Calculation of evaporative capacity and brine concentration

It is assumed that the evaporative capacity of the ith effect evaporator is G_{Di}. The temperature and latent heat of secondary steam are T_i and γ_i, respectively. The feed rate and concentration of the ith effect evaporator are L_i and X_i, respectively. The temperature and specific heat capacity of the current feed liquid of the ith effect evaporator are t_i and c_i, respectively. Then mass conservation equation for the ith effect evaporator in the operating condition of adverse current feeding could be obtained as:

$$\begin{aligned} L_i &= L_{i-1} + G_{Di} \\ L_i X_i &= L_{i-1} X_{i-1} \end{aligned} \quad (5)$$

The heat balance equation for the ith effect evaporator can be described as:

$$G_{Di-1}\gamma_{i-1} + L_i c_i t_i = G_{Di}\gamma_i + L_{i-1} c_i t_{i-1} \quad (6)$$

The phase equilibrium equation for the ith effect evaporator is stated as:

$$t_{i-1} = f(t_i, X_i) \quad (7)$$

3.2.3. Calculation of heat transfer area for each evaporator

According to the heat transfer rate equation, heat transfer area for the ith effect evaporator can be obtained as:

$$\begin{aligned} A_i &= q_i / K_i \Delta t_i \\ \Delta t_i &= T_{i-1} - t_i \end{aligned} \quad (8)$$

where q_i and K_i are the heat transfer quantity and heat transfer coefficient of the ith effect evaporator, respectively.

3.2.4. The amount of vapor produced by the brine flash tank and fresh water flash tank

The amount of vapor produced by the brine flash tank and fresh water flash tank could be calculated according to the flash equation of Rachford-Rice and phase equilibrium relationship in the flash tank. The detailed calculation equation of flashing amount is illustrated as follows:

$$\begin{aligned} G_{B,flashi} &= \frac{C_{P,B} \cdot \Delta T_i}{\Delta h_{v,i}} G_{B,i-1} \\ G_{D,flashi} &= \frac{C_{P,B} \cdot \Delta T_i}{\Delta h_{v,i}} G_{D,i-1} \end{aligned} \quad (9)$$

where $C_{P,B}$ is the specific heat of the liquid in the flash tank. ΔT_i is the heat transfer temperature difference. $\Delta h_{v,i}$ is the enthalpy. $G_{B,i-1}$ is the amount of the brine of the former effect evaporator. $G_{D,i-1}$ is the amount of fresh water of the former effect evaporator. According to the method, the amount of vapor produced by the brine flash tank and fresh water flash tank is shown in Table 5.

Table 5
The quality of evaporation, brine flashing and fresh water flashing

Effect number	The quality of evaporation (m^3/d) G_{Di}	The quality of fresh water flashing (m^3/d) $G_{Dflashi}$	The quality of brine flashing (m^3/d) $G_{Bflashi}$
1	718.42	1.71	/
2	660.12	6.15	12.00
3	635.61	10.27	23.71
4	591.83	14.28	39.15
5	586.61	18.10	36.81
6	599.08	21.84	36.38
7	630.71	25.62	35.97

Table 6
The operating parameters of steam jet ejector in TVC

Item	Pressure (kPa)	Temperature (°C)
Motive steam	800	350
Inject steam	10.37	46.5
Jet steam	32.52	71

3.2.5. The determination of TVC injection coefficient

The TVC system was used for pumping a small part of secondary steam produced by the seventh effect evaporator in order to make full use of motive steam. The biggest advantage for TVC is that the GOR will be increased under the certain quantity of motive steam. The saturated vapor pressure corresponding to the temperature of secondary steam produced by the seventh effect evaporator is 10.37 kPa. The performance parameters of the steam jet ejector are listed in Table 6.

According to the data in Table 6, the compression ratio and expansion ratio of the steam jet ejector can be calculated, and they are 3.13 and 77.15, respectively. Hence the injection coefficient could be obtained by theoretical calculation.

3.2.6. Performance of the MED device

The performance of MED device is exemplified by the industrial standard GOR for steam-driven MED system, which is the ratio of the distillate production to the steam input:

$$\begin{aligned} \text{GOR} &= G_D / G_S \\ G_D &= G_{D1} + G_{D2} + \cdots + G_{D7} \end{aligned} \tag{10}$$

where G_S is the mass flow rate of motive steam supplied to the evaporator.

3.3. The design calculation results

The detailed calculation data about the operating parameters for each effect evaporator and performance parameters for equipment are shown in Table 7. From the design calculation results it can be seen that the value of GOR is higher than the seven-effect MED-TVC desalination process presented by Hisham [23]. The major differences between the two process models were that the process model mentioned by Hisham [23] did not employ grouped feeding method and was not equipped with brine flash tanks. The motive steam pressure and temperature input of the two process models are also 1.0 MPa and 350°C, respectively. The maximum evaporating temperature of the two process models is also 70°C. According to the above operating conditions, the calculation GOR of process model presented by Hisham [23] is 8.9. The GOR of process model in this paper calculated by commissioning results is 10.3, increased by 15.7%.

3.4. 3D visualization design

3D visualization design means that the full design of technological process, mechanical equipment, piping system, control system, power distribution system and auxiliary system was conducted using 3D visualization software such as PDMS, Inventor, Promis-E, AUTOPLANT PI&W. 3D visualization network collaborative design not only could greatly shorten the design period and more intuitive, but

Table 7
The detailed calculation data about the operating parameters and performance parameters

Effect	1st	2nd	3rd	4th	5th	6th	7th	Condenser
T_i (°C)	67.5	64	60.5	57	53.5	50	46.5	/
T_{oi} (°C)	68.2	64.7	61.2	57.5	54.0	50.5	46.9	43.4
t_{fi} (°C)	54.02	54.02	54.02	43.00	43.00	43.00	43.00	30.00
Boiling-point elevation	0.70	0.68	0.65	0.46	0.45	0.44	0.44	0.00
X_i (ppm)	44.68	44.68	44.68	34.00	34.00	34.00	34.00	34.00
Outlet concentration of brine (ppm)	62.18	60.36	59.58	44.56	44.38	44.58	45.21	34.00
q_i×10^{-6} (kJ/h)	69.9	64.5	62.3	58.2	57.9	59.3	62.7	35.2
L'_f (m^3/h)	675.0							
L_f (m^3/h)	452.1							
L_B (m^3/h)	264.6							
G_D (m^3/h)	187.5							
M	0.75							
GOR	10							

Fig. 3. The detailed design process using PDMS.

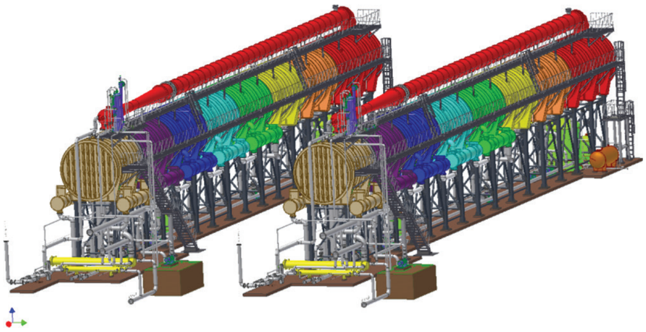

Fig. 4. The three-dimensional design of 2 × 4,500 m^3/d device in Indonesia using PDMS.

also could resolve the interference of pipeline. PDMS was set as an example to illustrate the 3D visualization process. The detailed design process using PDMS is shown in Fig. 3.

In the design process using PDMS software, the preparation work including project creating, establishment of component library and pipeline grade must first be completed. On this basis the modeling of mechanical equipment and piping system could be carried out subsequently. The accurate layout of the equipment including evaporators, condenser and flashing tanks is exhibited in Fig. 4.

Upon completion of the 3D model of the desalination plant, the checking of rationality of the whole computer-aided design could be implemented. The items of checking include possessing integrity of all the equipment and instruments, reasonable of arrangement of devices, interference judging between devices and consistency of the design data. At last all kinds of construction documentations including installation and construction drawings could be exported from the draft module of PDMS.

4. Installation and commissioning

4.1. Installation method

The desalination host was installed on the bracket with bolt connection. There are in total 34 pillars standing in 17 rows to support the system. It is suggested that the equipment could be installed in the following order: (1) Inspect foundation and embedded parts; (2) install supporting pillars; (3) weld rod between the posts; (4) install containers and water pumps between shelves; (5) install evaporators; (6) weld evaporators; (7) install flash tanks; (8) install walkway platform, handrail and ladder; (9) install steam ejector and main steam pipeline; (10) install the various types of pipe; (11) install instruments and (12) install electrical and control equipment.

Note that the installation sequence mentioned above is not static in the construction site. Therefore, the practical installation sequence should be determined according to field condition, equipment size, progress, and so on. The general rule is to avoid inadequateness of installation space for the subsequent equipment and interference each other after adjustment. The installation site of 2 × 4,500 m^3/d MED device is shown in Fig. 5.

Fig. 5. The installation site of 2 × 4,500 m^3/d MED device: (a) hoisting of evaporator and (b) the panorama of desalination host after installation completely.

4.2. Debugging and testing

The debugging test projects mainly contain hydrostatic test, airtight test and performance test of subsystems (such as control system, power distribution system etc.). The integration test of the whole system was started after the debugging of the subsystems. The motive steam and raw seawater will not be fed into the desalination evaporators until debugging of the subsystems meet the design requirements at the stage of integration test. A continuous 168-h performance was tested to assess the indicators of the device comprehensively.

The measuring parameters sensors, including temperature, pressure, flow rate, fluid level, online conductivity and pH, were used for testing the operating parameter. Motive steam temperature and pressure fluctuations affected the measurement accuracy of the steam flow rate. In our experiment, the orifice plate flowmeter is used to measure steam flow rate with temperature and pressure compensation to ensure a measurement error of less than ±0.1%. Product water quality was monitored by using an online conductivity meter and a pH meter installed on the product pump outlet. The host computer records and stores all in situ operation data automatically. And it also has the history data curve automatic record, storage and archiving function. Two data query methods trends display and report are designed using server SQL 2000 as the database of data archiving. Fig. 6 shows the monitoring screen of the upper computer in the device.

The testing result of raw seawater temperature is shown in Fig. 7. The testing results about flow rate of total raw seawater, feed seawater into the desalination evaporators, production fresh water and concentrated brine are shown in Fig. 8. The collected data about the conductivity of production water and the condensate water is shown in Fig. 9. The testing data about flow rate of motive steam supplied for evaporators and system GOR is shown in Fig. 10.

Figs. 7 and 8 show that the total raw seawater feed rate changes with its temperature. It can be clearly seen that the total raw seawater feed rate had increased by nearly 4% when the temperature of seawater has risen by about 1°C at the stage of 60–84 h. This is because that the cooling water used for condensing the secondary steam produced by the last effect evaporator will be increased due to the raw seawater temperature rise. The curve of 2, 3 and 4 in Fig. 8 shows that the production water remained about the same, and the discharged brine flow increased correspondingly when increasing the total raw seawater feed rate at the stage of 75–118 h. Results of data analysis show that the design of the sprinkle density of each evaporator is reasonable and the heat transfer performance behavior can be reflected adequately. In this

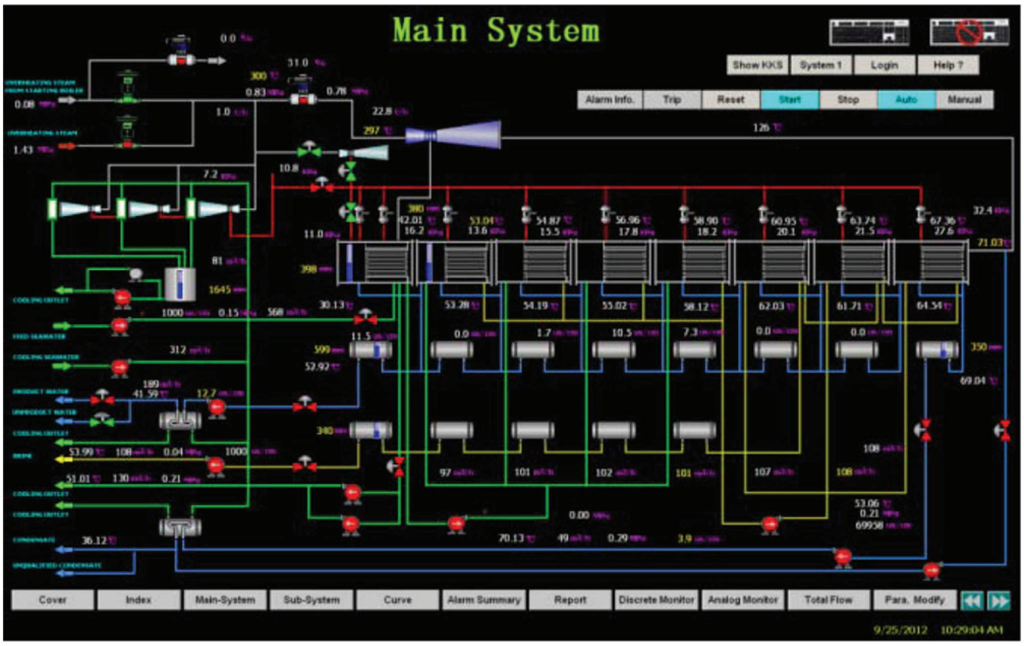

Fig. 6. Device performance testing monitor screen.

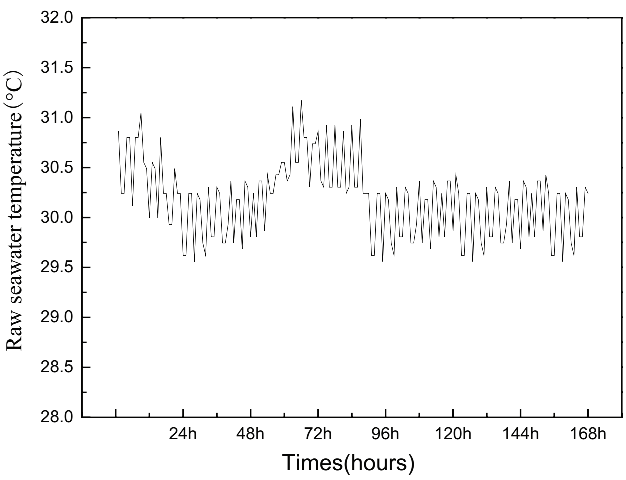

Fig. 7. Raw seawater temperature.

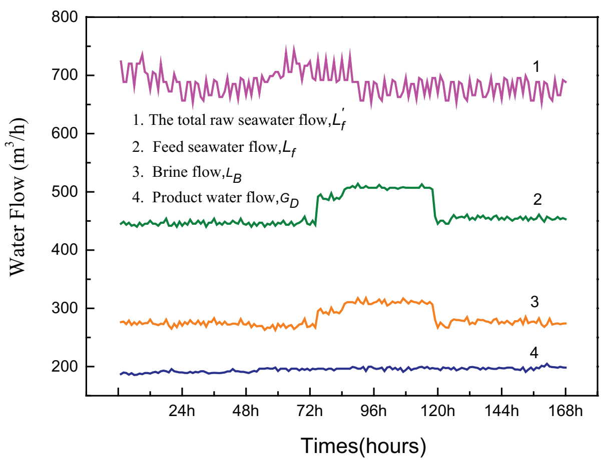

Fig. 8. Flow rate of feed seawater, product water and brine.

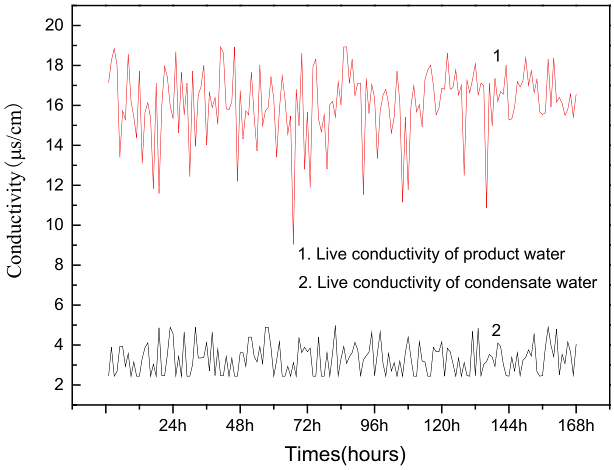

Fig. 9. Live conductivity of production water and condensate water.

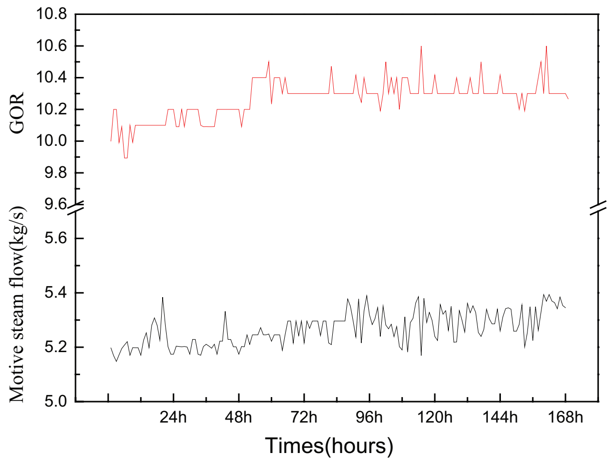

Fig. 10. The testing data about flow rate of motive steam and GOR.

case the production water could not be enlarged by a process of increasing the spraying volume of evaporators.

The salinity of raw seawater always kept the level of 33,000~34,000 mg/L during the test. And the average raw seawater temperature is 30.2°C, as shown in Fig. 7. From Figs. 8 and 9 it can be seen that the average production capacity of a single unit is 196.4 t/h (4,712.4 t/d); production fresh water conductivity is 15.9 μs/cm (7.98 mg/L). The first effect condensate water conductivity is 3.43 μs/cm.

It can be seen from Fig. 10 that motive steam fluctuated slightly during the test, basically maintaining the pressure of 0.8 MPa and temperature of 350°C. And consumption of motive steam is about 18.98 t/h. GOR of the device could be obtained is 10.3, higher than the design value of 10. After analysis, this is mainly due to the following two reasons. One is that the heat transfer coefficient within the evaporator is affected by many factors. The value of the heat transfer coefficient adopted during the process calculation is more conservative than that of actual heat transfer process. The other one is that the structure of seven-effect evaporators was arranged in the same way in order to reduce the cost of raw materials and manufacture fee. So that the actual number of heat transfer tubes installed in some evaporators is slightly higher than the results of design calculation.

5. Conclusions

(1) According to the motive steam quality and raw seawater condition, technical process for INDRAMAYU desalination is designed to use the coupling technology of grouped feeding method, brine flash tank and freshwater flash tank comparing with conventional MED-TVC system. A process calculation model of an integrated technical process combining the technology of flashing, multi-effect and TVC for improving the thermal efficiency of the desalination system was presented. The mathematical model was calculated using the self-designed software "MEDGYV2010". The field debugging results show that the GOR of the system was increased more than 10% than seven-effect MED-TVC desalination process published in former literature.

(2) The collaborative design of technological process, mechanical equipment, piping system, control system, power distribution system and auxiliary system was conducted through the software of Inventor, PDMS and Promis-E. Therefore, the design cycle was shorter, and the fund was much saved.

(3) The MED was continuous running not less than 168 h at full capacity for reliability test. And under the condition of the motive steam pressure 0.8 MPa, motive steam temperature 350°C and salinity 33,000~34,000 mg/L of raw seawater, the GOR of the MED system could reach to 10.3. During debugging period the average quality of production fresh water is 7.98 mg/L. All the performance indexes meet the design requirements. The debugging results show that developed model and design parameters for process calculation are reasonable.

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Nomenclature

A_i — Heat transfer area for the *i*th effect evaporator, m^2
c — The specific heat capacity of seawater feeding into condenser, J kg^{-1} °C^{-1}
c_i — The specific heat capacity of seawater feeding into the *i*th effect evaporator, J kg^{-1} °C^{-1}
G_D — The production capacity of desalination device, m^3 h^{-1}
G_{Di} — Evaporation capacity of the *i*th effect evaporator, m^3 h^{-1}
G_S — The mass flow rate of motive steam supplied to the evaporator, m^3 h^{-1}

K_i — The heat transfer coefficient of the *i*th effect evaporator, J $(m^2)^{-1}$ °C^{-1}
L_f — The demand for raw seawater of desalination evaporators, m^3 h^{-1}
L'_f — The total raw seawater flow of desalination device, m^3 h^{-1}
L_c — The quantity discharged into the sea as the cooling water, m^3 h^{-1}
L_{vp} — The amount of raw seawater consumed by steam jet vacuum pump, m^3 h^{-1}
L_{tf} — The total intake of seawater, m^3 h^{-1}
L_i — The feed rate of the *i*th effect evaporator, m^3 h^{-1}
L_B — The discharged mass flow of brine, m^3 h^{-1}
q_i — The heat transfer quantity of the *i*th effect evaporator, J h^{-1}
T_i — The temperature of secondary steam produced by the *i*th effect evaporator, °C
T_{oi} — The outlet temperature of the seawater flowing out of the *i*th evaporator, °C
t_f — The inlet temperature of the seawater feeding in the condenser, °C
t_o — The outlet temperature of the feed liquid in the condenser, °C
t_{fi} — The inlet temperature of the seawater feeding in the *i*th evaporator, °C
X_i — The concentration of fluid liquid feeding in the *i*th effect evaporator, ppm
B — The concentration ratio of desalination device, ppm
γ — Latent heat of the secondary steam, J kg^{-1}
γ_i — Latent heat of the secondary steam produced by the *i*th effect evaporator, J kg^{-1}
μ — The injection coefficient of the steam jet ejector

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