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Optimized Marine Fresh Water Generator Control System

Optimizirani sustav upravljanja generatorom slatke vode iz morske

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Summary

The introductory part of this paper offers an overview of approaches to the management of marine fresh water generator and points out the most important factors influencing the processes. The second part deals with operation time and total overhaul time both influenced by evaporation intensity. Comparison and simple calculation are made of several distinct modes of operation assuming days in voyage and hours necessary for overhaul. Next section gives a thermal analysis of the processes, resulting in energy balance equation that could be used as a base for the optimal control system for one single-stage unit. In fact, the suggested control system is based on the energy balance equation that is given in this section. In the fourth part the analysis of the most important operational values is made. The changes recorded on the six-channel plotter are used to evaluate the suggested control system. The paper gives an example of optimal control system for the single stage fresh water generator and suggests further research.

KEY WORDS

energy
control system
marine fresh water generator
optimization

Sažetak

Uvodni dio ovog rada nudi pregled pristupa upravljanju generatorom slatke vode iz morske vode i ukazuje na najvažnije čimbenike koji utječu na procese. Drugo poglavlje bavi se vremenom rada i ukupnim vremenom obnavljanja, pod utjecajem intenziteta isparavanja. Usporedba i jednostavan izračun napravljeni su od nekoliko različitih načina rada, koji podrazumijevaju dane u putovanju i sate potrebne za obnavljanje. Sljedeće poglavlje daje toplinsku analizu procesa, što rezultira jednadžbom energetske bilance, koja bi se mogla koristiti kao osnova za optimalan sustav upravljanja za jednu jednostupanjsku jedinicu. Zapravo, predloženi sustav upravljanja temelji se na jednadžbi energetske bilance, koja je dana u poglavlju. U četvrtom poglavlju vrši se analiza najvažnijih operativnih vrijednosti. Promjene zabilježene na šestokanalnom crtaču koriste se za procjenu predloženog sustava upravljanja. U radu se daje primjer optimalnog sustava upravljanja za jednostepeni generator slatke vode i sugeriraju se daljnja istraživanja.

KLJUČNE RIJEČI

energija
sustav upravljanja
generator slatke vode iz morske vode
optimizacija

1. INTRODUCTION / Uvod

Although the process of fresh water production by distillation method is well known and analyzed in the scientific journals, the significance of the distillation plant on board ship gives an opportunity for further improvement [1, 2]. The distillation plants are important for cargo ships but, even more for large passenger cruisers. Those ships consume large quantities of fresh water. The amount rises to 300 liters per person daily and more, and there are engines as well.

Scientific results could be used to improve the control system and, consequently to reduce the price of the produced water or to improve its quality or both. Since on board ships waste heat is mainly used, apart from small consumption of the electric energy for the sea water and distillate pumps, the price of production is the price of crew members working hours consumed for occasional cleaning and the price of expendable material used for cleaning [1, 2]. Used material is mainly acid solution used to dissolve scale created on the evaporator surfaces during operation hours.

The efficient control system [3, 9, 10] of the distillation process should increase the maximum continuous capacity and to decrease operation costs. It would be time consuming to engage engine officer to control the process of distillation personally, so it is clear that a control system must be implemented to accomplish these tasks.

The analysis of processes, thermodynamic parameters, measured and regulated values [1, 2, 3, 4, 9, 10] point out the following:

- although the evaporator heat inlet and the condenser heat outlet change in time, by fixing the regulating valves position both could be considered constant – the changes depend on the regulator, probably PID, characteristics
- with the above presumption the quantity of produced vapor and consequently of produced distillate depends mainly on pressure changes in the vessel, i. e. upper and lower values of pressure switch that opens and closes the vacuum breaking valve

- almost every measured parameter shows sinusoidal change exactly in accordance with the change of pressure, or precisely vacuum in the vessel, but some show deterioration with operating hours
- both short- and long-term changes in the process affect the quantity and quality of the distillate because they affect the speed of scale formation
- the scale formatted on heating surfaces reduces the plant's capacity, the pressure drop in the heat exchanger channels is increased, the heat necessary for the evaporation is increased and the temperatures are increased resulting with even faster scale formation and, the quality of distillate could be decreased.

The control algorithm should use the above listed facts, but much more, especially fault propagation through the process [11, 12, 13, 14]. Namely, abnormal changes of measured parameters or too fast changes should trigger the control system to give an alarm or to start the protection procedure or to give a diagnosis.

Up to day the control of distillation process includes several tasks: the amount of heat is preset by setting the position of by-pass throttling valve, in similar manner the amount of condensers cooling sea water is preset by throttling valve, the pressure in the vessel is determined with two setting points for pressure breaking valve opening and closing and, the complete operation is consequently controlled through produced fresh water salinity. Other checks are performed periodically by an engineer.

Obviously, it is fairly easy to understand and simple but, it is surely not the optimized operation because the velocity of scale formation and the influence of scale on total capacity and produced water quality are not considered.

2. THE EFFECT OF OVERHAUL TIME ON THE CAPACITY / *Utjecaj vremena obnavljanja na kapacitet*

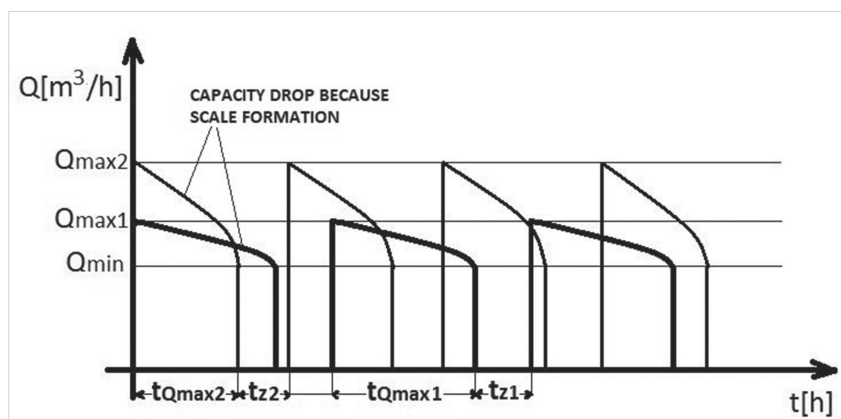
The diagram shown on graph 1 represents the changes in the capacity of the plant with the operating hours and the maximum capacity set point. The diagram stands for the single stage vacuum plant that could be found on almost every ship having diesel engine propulsion. There are three important elements such plants have: evaporator, demister and condenser, and several auxiliary elements or subsystems: brine rejection, vacuum management and distillate collection including the

salinity check. Some technological differences are possible. Occasionally, plants could have only one ejector instead of two, while in some cases sea water is preheated being used as condenser's cooling fluid. On the steam turbine propulsion ships not vacuum, but low or even medium pressure plants are used, and steam is used as heating agent. In case large capacities are needed multistage plants are used. Those differences do not change the process basics.

Many factors affect the distillation processes: environmental, technological and operational. That is why the authors decided to present on Graph 1 the qualitative changes only. Perhaps the diagrams are not precise enough, but they show the basic changes of capacity because of scale formation and the necessary time for overhaul - t_z . For the exact quantitative relations waste number of ship plants and parameters should be analyzed. Even so, the validity of obtained data could be questionable, because it still depends on too many factors. The actual capacity Q_{max1} and Q_{max2} stand for two typical modes of operation, the second being the maximum designed capacity of the plant. The overhaul periods t_{z1} and t_{z2} are set as equal in both of the cases, although this could be questionable for a variety of reasons.

In the period during which desired and set plant's capacity is decreased to the lowest permitted one - Q_{min} , being the one that still satisfies actual consumption, the following factors are of importance: construction characteristics of the evaporator and condenser and their condition according to the exploitation, surrounding condition, i. e. sea water temperature and salinity, heat inlet and outlet settings, vacuum breaker valve or vacuum in the vessel control settings and other. The longitude of the nonoperational period is affected by the scale thickness on evaporator surfaces, the quantity and concentration of acid solution applied, capability and training of crew members and other. The nonoperational periods during sailing through contaminated coastal waters are not considered, but the periods necessary for scale removal from heating surfaces are.

With all restrictions the diagram on Graph 1 has, for certain distillation process control system functions considerations could be useful. The diagram shows two distinct modes of operation: first, when lowest capacity is set, and second, when maximum obtainable capacity for given surrounding conditions and plant's operating condition is set. In both scenarios there is a small drop in capacity caused by scale formation on the



Graph 1 The plant's capacity over time dependence
Grafikon 1. Kapacitet postrojenja tijekom vremenske ovisnosti

heating surfaces, the difference being faster scale formation in the second scenario.

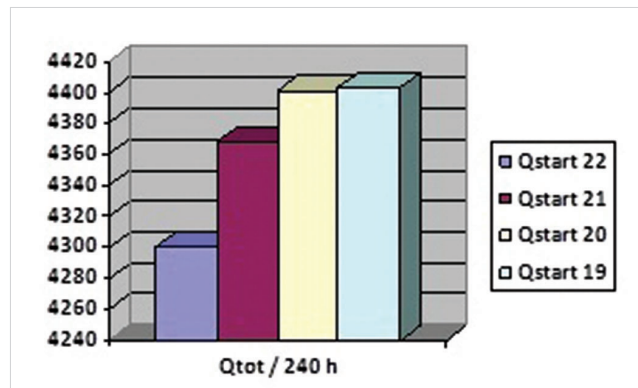
In the second scenario more heat is introduced in the process of evaporation or high vacuum is created in the vessel, hence the temperature of sea water undergoing process of evaporation is higher, vapor bubbles are created on lower position in the evaporator channel, more vapor bubbles are created usually combining in a few larger ones, a very narrow brine layer with increased salinity remains on the surface wall [1-8, 15]. Shortly, the evaporation is increased and scale formation on hot surfaces is also increased. Side effect is that quality of produced fresh water is reduced too. Theoretical explanation is that increased evaporation results in large number of smaller brine droplets demister cannot efficiently collect, they pass to the condensers part of the vessel and consequently, the distillate's salinity is increased.

Because of several reasons mentioned earlier in the paper, it is impossible to predict exact number of operating hours, but from marine practice it is known that in tropical environment having higher temperatures where larger amount of water is consumed and obviously higher production is needed, evaporator surfaces must be cleaned every 48 to 72 hours, while in moderate climates this should be done only every few days. The thickness of the scale could also be increased resulting in increased overhaul time.

Hence, although the increase in evaporation results in immediate increase of distillate production, because of often stoppages needed for cleaning the evaporator surfaces, the process production is in fact decreased. Sometimes the maximum production is necessary, but in most of the cases more meaningful is long term process production that calculates both the production and stoppage periods.

Several practical situations will be compared. Fresh water generator with maximum capacity of 22 t/h is selected for analysis. The minimum capacity that satisfies ship's need is 18 t/h. Assumed voyage time on open sea is 10 days or 240 hours. In the first case operation starts with maximum capacity, it drops to minimum allowable capacity during 48 hours, and stoppage for cleaning that lasts for 6 hours follows. The second case starts with 21 t/h, it drops to minimum during 56 hours, and a stoppage for 4 hours follows. In the third case operation starts with 20 t/h, it drops to minimum during 76 hours, followed by stoppage of 3 hours, while in the last case operation starts with 19 t/h and stoppage time is 2 hours. Operations in every case are repeated until expiration of voyage time, because the plant is stopped during sail through contaminated coastal waters. It is clear the selected operating and overhaul periods are instructive only. The operating period of 48 hours is selected as typical for tropical seas voyage when, it is well known, an engineer need to shut down the operation for scale removal. The opposite situation would be a normal one, with more operating hours, while two intermediate scenarios are selected randomly.

Results of this simple analysis the authors presented on Graph 2. Simplified mathematical model shows that for starting and operating conditions during 10 days voyage the highest process capacity is accomplished with the lowest starting capacity of 19 t/h and the operation period of nearly 10 days and the lowest with the highest starting capacity.



Graph 2 The plant's theoretical capacities for different starting and operating conditions

Grafikon 2 Teoretski kapaciteti postrojenja za različite uvjete pokretanja i rada

Increase in heat inlet and vacuum in the vessel results with increase in evaporation and plant's capacity. The reduction of those parameters results with decrease in capacity. It seems the first mode of operation is better, but from earlier analysis it is obvious that this is not so. Furthermore, the increase of vacuum in the vessel will positively affect the evaporation but it will diminish the condensation process taking place in the same vessel. Another setback is creation of brine droplets and their separation from fresh water molecules. It is well known that separator (demister) operates poorly when large number of small droplets is created, meaning that the quality of distillate is decreased.

In modern fresh water generator types corrugated plates are used for both evaporators and condensers, but even more, plates are made in one piece. When combined with rubber gaskets evaporator, demister and condenser channels are created, as schematically shown on Figure 1. The type of exchanger surfaces would not in any way affect the processes mentioned before. Besides technical layout of the plant and its piping, the Figure shows inlet and outlet signals of the control unit.

The heating fluid flow through the evaporator and the vacuum in the vessel have the main influence on the evaporation process. Management unit measures the pressure (PT) and temperature in the vessel (TT) and of the casing respectively, and the distillate's salinity (ST). In accordance with measured values and logic implemented the unit will act on by-pass valve 1 and vacuum breaker valve 3. If salinity transducer detects the value is too high, the control system would open valve 5 releasing the fresh water with increased salinity to the engine room bilge or in the clean bilge tank or back to the vessel.

3. OPTIMIZED CONTROL SYSTEM / Optimizirani sustav upravljanja

Let us repeat the reasoning from before. The main effects on the distillation process have: heating fluid flow through the evaporator and cooling fluid flow through the condenser, both affected by heat transfer coefficients that are deteriorating with operation hours, the temperature differences between the fluids in those heat exchangers, and the pressure in the vessel.

If maximum cooling fluid flow through the condenser and proper vacuum ejector operation is assumed, the utmost effect

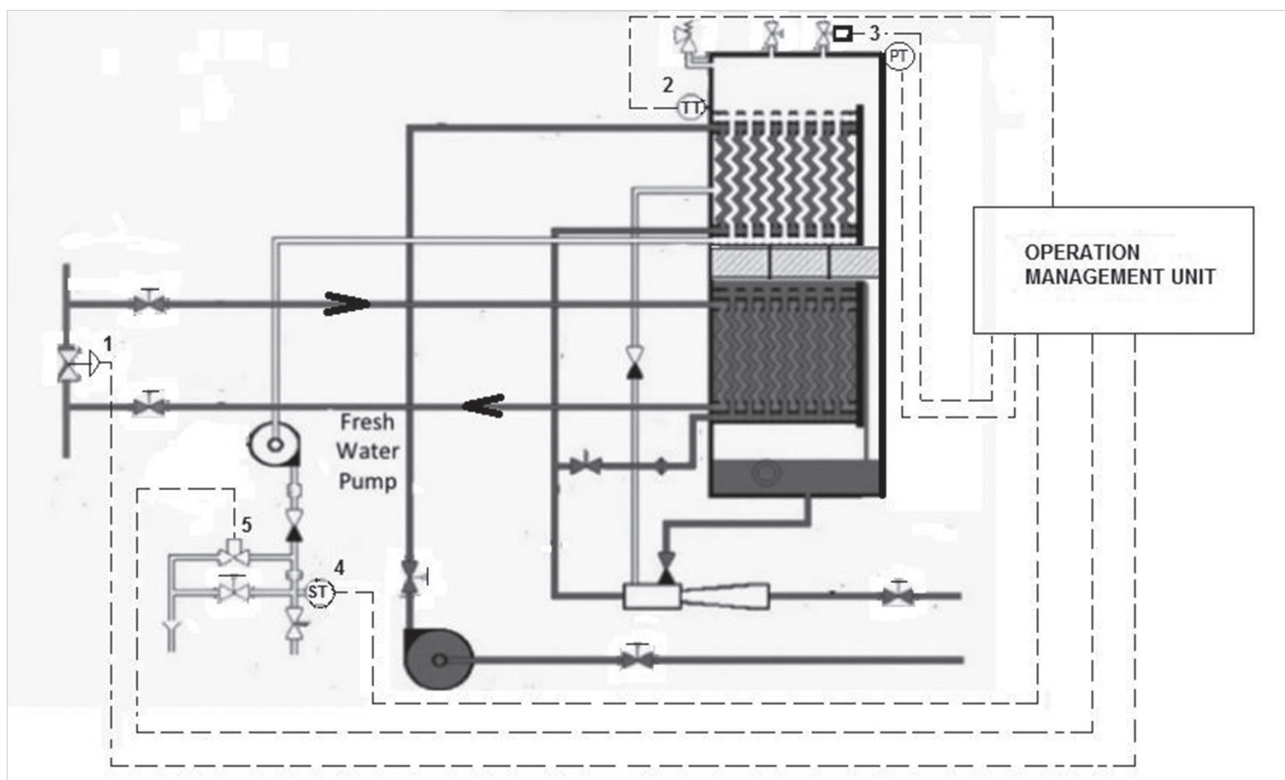


Figure 1 Fresh water generator and control system
 Slika 1. Generator i upravljački sustav slatke vode

would have the temperature difference between the cooling sea water, having the surrounding temperature or being slightly preheated, and the fresh water saturation temperature depending on the pressure in the vessel. There is no objective reason to reduce the cooling water flow, except there is a problem of low flow through the main engine fresh water cooler. The presence of non-condensable gases in the vessel would reduce the condensing effect, and they are removed by the ejector. The temperature difference between the heating fluid and the heated sea water is most important parameter for evaporator performance, but not the only one.

For practical reasons one could assume certain temperature values. The maximum temperature in the process is the temperature of the heating fluid, being the high temperature main engine cooling water, and is determined by the regulating equipment of the system. Usually, the set point of high temperature fresh water exiting the main engine is 80°C. The lowest temperature of the process is the sea water inlet temperature, and for 80 up to 90% of the ships it varies from 10 to 20°C.

The short explanation of the schematic representation in Figure 1: the vessel contains two heat exchangers, the evaporator at the bottom and the condenser at the top of it, with demister in-between. There is one ejector only, sucking both brine and gases from the vessel. The sea water enters in the condenser where it preheats, and then a part enters the evaporator, while a part acts as driving fluid of the ejector. The condensed fresh water is sucked by the distillate pump, as it accumulates at the condenser's pan. The quality (the salinity) of the distillate is controlled by a sensor 4, and if inadequate it is released by opening of valve 5 to the engine room bilge (or in some cases in the vessel where it is expelled as brine). The evaporation intensity is controlled by the vacuum control valve 3, in accordance with the vessel's casing temperature signal from the sensor 2.

The empirical Antoine's equation could be used to determine saturation temperature of the liquid according to the pressure. When condensation and evaporation temperatures of fresh and sea water are compared, the second one is slightly higher. A term boiling point elevation (BPE) is used, and it represents the increase of sea water saturation temperature over fresh water saturation temperature for the same pressure. Since there are temperature differences between two fluids both in the evaporator and the condenser, i. e. dT_{evap} i dT_{cond} and that they represent, together with the respective fluid flows, main heat exchange generators, it is clear the effect of evaporation would be increased, and the intensity of condensation decreased with decrease of the pressure in the vessel. It should be possible to determine for every surrounding temperature the optimal pressure in the vessel, although there will be a small oscillation of pressure in accordance with the pressure control system.

Fig. 2 explains the processes in evaporator and condenser channels. For the simplicity reasons these channels are drawn as vertical and horizontal tubes. The seawater enters at the bottom end, a part of water evaporates, a part of brine is carried over as small droplets and, the rest is released as brine. The tube heights or precisely the water in the tube heights over temperature ($z - T$) diagram on the right part gives an explanation of what happens in those tubes. The angled line T_s represents the increase of saturation temperature with sea water or brine depth in the channels. The value T_{s0} stands for the saturation temperature according to the absolute pressure in the vessel and T_s increases with liquid heights in the channel. The curve T_f shows the change of actual liquid temperature as it flows upwards through channels. Theoretically, at certain level those two temperatures would equalize, and the evaporation would start, i. e. the first vapor bubble would be created. But, the evaporation starts little bit above this level because there must

be a temperature gradient to drive the mass transfer through the bubble border. This is shown with the value ΔT_{min} . The dashed line shows that temperature would remain constant and would not asymptotically equalize with the heating fluid maximal temperature of 80°C.

The upper part of the Fig. 2 shows the condenser process. Sea water passes through the horizontal channels. The vapor mixed with brine droplets is condensed on the outer surface. The saturation temperature remains constant because it depends on the vessel pressure only. The temperature of the vapor would decrease asymptotically to the cooling (sea water maximal inlet temperature according to the classification society regulation) but, after condensation starts it remains constant.

The Figure explains why the increase of vacuum in the vessel while acting favorably to evaporation would act quite the opposite to condensation. Increasing the vacuum or lowering the absolute pressure in the vessel graphically would mean the line representing saturation temperature would move to the left, resulting in the earlier start of the evaporation but the condensation would be retarded.

The control of the complete procedure should take into consideration a fine balance of all the energies entering and leaving the vessel and the absolute pressure in it, particularly if higher process capacities are wanted. The total energy balance equation for the plant given in Fig. 1 is

$$\Delta Q_{heat/HT} + U_{SW} - (\Delta Q_{cond} + U_{brine} + U_{dest} + U_{gas} + Q_{rad}) = m_{cas} c_{cas} \Delta t_{cas} \quad (1)$$

The values in the expression (1) from the left to the right are: $DQ_{heat/HT}$ heat inlet introduced in the process with main engine high temperature cooling water, U_{SW} inlet sea water internal energy, DQ_{cond} heat rejected from the process by condenser's cooling sea water, U_{brine} rejected brine internal energy, U_{dest} produced distillate internal energy, U_{gas} internal energy of non-condensable gases removed from vessel, Q_{rad} heat radiation losses to the surrounding (engine room), m_{cas} mass of the plant's casing; c_{cas} specific heat of the casing material; Dt_{cas} the temperature change of the casing itself. A heat introduced in the vessel with the air that enters after vacuum breaker valve opens could be neglected. As compared to other values, the last two on the left side of the equation are of lower magnitude, and as such could also be neglected.

During the beginning of the operation the heat introduced in the process is higher than the heat removed from it, resulting in increase of casing temperature. The casing temperature would asymptotically approach the upper limit. After stationary condition has been reached, there would be only small disturbances caused by surrounding temperature changes, control system characteristics etc.

The expression's (1) simplification gives an insight of possible simpler and cost-efficient control system application. The precision in main parameters regulation would in the same time not be lost and the quality of produced distillate would not deteriorate. The simplification results in:

$$\Delta t_{cas} = K \Delta E \quad (2),$$

where K is a constant including physical values of casing material, and DE is a difference of heat inlet and outlet of the process.

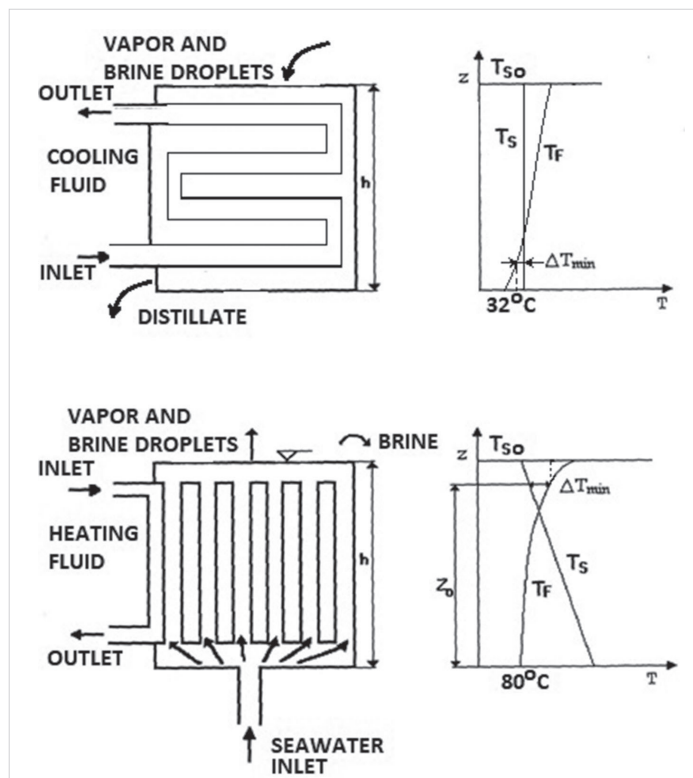


Figure 2 Evaporation and condensation in their respective channels
Slika 2. Isparavanje i kondenzacija u odgovarajućim kanalima

4. SIMULATION OF THE THERMAL PROCESSES IN THE PLANT / Simulacija toplinskih procesa u postrojenju

Value of DE changes with transient outer and inner conditions:

- heating fluid flow is constant in time according to the regulating by-pass valve position, but temperature varies according to the main engine power and the characteristics of the system that regulates the temperature, the heat transfer coefficient changes in time due to the scale formation in particular
- sea water flow should be considered as constant, but its temperature changes with the movement of the ship
- the same stands for condenser's cooling sea water but, moreover heat transfer coefficient also changes in accordance with non-condensable gases or other impurities presence
- heat rejection with brine removed from the vessel depends on the first condition and the evaporation intensity
- heat rejection from the process with amount of distillate discharged also depends on the evaporation intensity.

Simulation was carried over on the engine room model created by Kongsberg Norcontrol, in every respect like the one shown in Fig. 1. The key values have been measured and recorded. Recorded values are given in Graph 3. Plot window is set to 20 minutes.

Six-channel plotter was used. The changes are recorded during 20 minutes period (from 32nd till 52nd minute of operation). During that period the position of the by-pass regulating valve was gradually changed. Vertical lines mark the moment when the valve position was in fact changed. The following parameters were recorded: light purple represents inlet sea water salinity (it is constant during the recording time), ocher represents the salinity of the rejected brine, green represents the distillate

salinity, purple represents the amount of produced distillate, blue represents the (absolute) pressure in the vessel and black represents the temperature of discharged distillate.

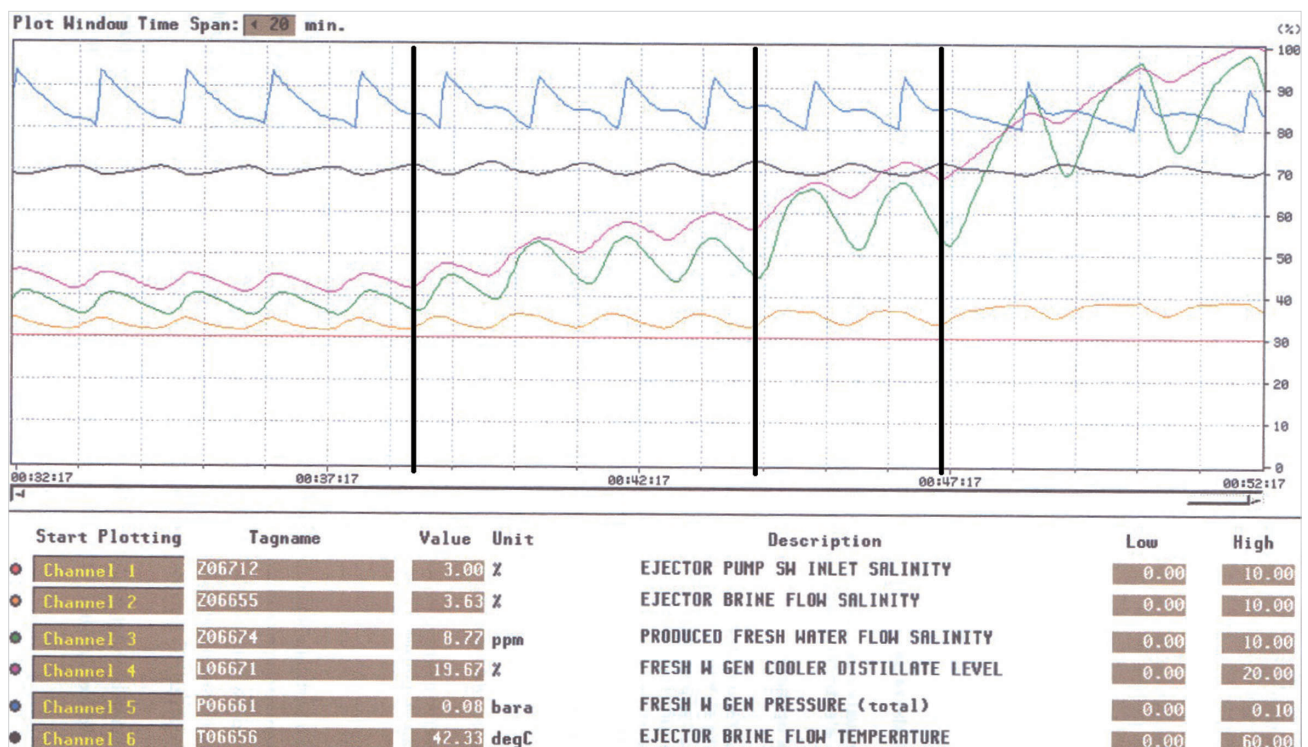
The sinusoidal change of every measured parameter could clearly be seen, except inlet sea water salinity. From the plant's operation explanation presented before, the generator of those sinusoidal changes is vacuum breaker valve, i. e. changes of the pressure in the vessel. The trigger points of the vacuum breaker valve are 91% of vacuum or 0,09 bar of absolute pressure when it closes and 92% of vacuum or 0,08 bar of absolute pressure when it opens. When vacuum breaker valve opens there is a sudden rise of absolute pressure in the vessel and, after it closes, the pressure slowly decreases.

Other dependable parameters follow the same change. Another major influence has change in position of the heating fluid by-pass valve. The vertical lines show the moment of change in the valve position, i. e. the valve was slightly closed, resulting with the increase of heating fluid inlet. The curves show slight increase of brine's salinity and temperature, while at the same time there is a sudden increase of distillate production, and unfortunately its salinity.

5. CONCLUSION / Zaključak

Of every changeable parameter affecting the plant's operation, especially the distillate production and salinity, the most important are heating fluid flow to the evaporator and the vacuum in the vessel. If proper operation of the vacuum management system is assumed, the value of the vacuum would change between the two set limits, the pressure would have a sinusoidal change and every dependable parameter would change accordingly.

It is clear the major increase of distillate production can be accomplished with increase of heating fluid flow to the



Graph 3 Main measured parameters plotted [1, 2]
Grafikon 3. Učrtani glavni izmjereni parametri [1, 2]

evaporator. Unfortunately, the consequence of such operation is distillate of higher salinity.

The energy balance analysis shows the dependence between the energy of the process and the temperature of plant's casing. In accordance with the expression a simpler and cost-effective management system and advanced information algorithm could be implemented without losing necessary distillate capacity or increasing its salinity.

Other mathematical models should be used to verify that increase of heat inlet to the process causes faster scale formation, increases the operation costs due to crew members working hours and due to material expenses, and consequently reduces the process capacity of the plant. Also, a model of scale formation dependence on heating fluid and evaporating brine temperatures should be designed to determine the optimal process procedures.

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List of symbols

c [$\text{J/kg} \cdot \text{K}^\circ$] specific heat capacity
 m [kg] mass
 DQ [J] heat difference
 Q [J] heat
 Dt [$^\circ\text{C}$] temperature difference.
 U [J] internal energy

Indexes

brine – water and salt concentrated solution
cas – casing
cond – heat input into the condenser with the cooling seawater
dist – distillate
gas – exhaust gases
heat/HT – heat input with the main propulsion engine high temperature cooling water
rad - heat lost by radiation into the engine room
SW – sea water