Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.21522

95 (2017) 180–185
November

Analysis of thermodynamic and technological basics of the marine fresh water generator model

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Received 9 May 2017; Accepted 4 October 2017

ABSTRACT

The paper deals with the work of the single-stage vacuum fresh water plant usually used on board cargo ships, namely with the influence of the thermodynamics process and of the technological arrangement on the performances. The distillation method has been well known since the ancient civilization, but there is still room for the improvement of the process depending on the selected criterion. Furthermore, the arrangement of the plant, including all control and regulation elements, has an impact on the process running and, after all, on the quality and quantity of the generated distillate as well as on the price of the installation. As a conclusion, a simple mathematical analysis has pointed to the key parameters that have to be monitored during the work as well as to the possible optimal control system, as it has been proved by simulating the work and registering the changes in the stated parameters during variable working conditions. The result of the paper could lead to a simpler and cheaper governing system, to the better quality of the distillate and more operating hours of the equipment.

Keywords: Analysis; Distillation; Mathematical model; Optimal process; Single-stage vacuum plant; Thermodynamic and technological elements

1. Introduction

Although the fresh water generation process by distillation of the seawater has been well known since ancient times and many research papers with a different approach to this theme have been published in scientific journals, the importance of a distillation plant on board a ship opens new possibilities for further researches. The scientific papers published previously deal with stationary equipment while on board implemented equipment has somewhat specific demands. Some of them being: in case of failure there is no help from shore, so it should be possible to repair the equipment by crew members and with the materials on board; a governing system should be reliable and simple, so that in case of failure an engineer officer should be able to detect the point of origin and, if unrepairable, to lead the process manually; short overhaul time, so that fewer operating hours would be lost.

The distillation method prevails over the other desalinization methods [1] as it is connected with the more frequent type of ship main propulsion engine – the diesel engine. The equipment is a low thermal one, but it could not depend on solar energy [2] – there is an abundance of thermal energy from cooling engine systems. The distilled water on board cargo ships is used for propulsion systems (engine cooling systems and boiler water systems) and as domestic water for crew and passengers. The produced water is accumulated in common tanks and from there distributed to a specific consumer. In every particular case, it is prepared as demanded by the consumer. An engine producer demands application of certain additives, a boiler producer demands different additives, while in case of human consumption the water is disinfected (e.g., with ozone) and mineralized. The equipment is never used in coastal waters because of the possibility that

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sea water being polluted with chemicals and biological contaminants. Two are the criteria for its selection: the capacity of the plant and the price of the generated product, namely of the generated water [3].

The plant capacity has to be monitored during a longer period of time, and to estimate the price of the generated water, the investment and exploitation charges have to be considered. The running of the process as well as the role of the marine engineer or of the automatic operation system substituting him is important in both the cases.

The automatic operation system cannot substitute the marine engineer in full. The system can fail occasionally due to a malfunction. Imperfection of the system itself can also be a cause of failure as all possible faults in the running of the plant cannot be predicted in their entirety [4,5]. Nevertheless, automation of the ship power plant has been improving further on, so that it has been applied not only to the main components of the ship power plant but also to the increasing number of auxiliary plants and systems as well.

The proper running of the distillation process automatic operation system will depend primarily on the estimation of the essential thermodynamic parameters that affect the process and on the technological criteria of the plant. The analysis of the influence has been carried out based on the plant simulated in the Kongsberg Norcontrol engine-room PPT 2000 simulator. The thermodynamic properties of the sea water slightly differ from the properties of the fresh water and this represents a problem [6,7].

The intention of the paper is to establish the changes of the operation during transitional period and, as a consequence, to determine the most important parameters that should be monitored and regulated. There could be a number of maintenance and governing approaches, but the optimal ones should increase the quality and the production [8,9].

2. Analysis of thermodynamic and technological basics

The simulated plant corresponds in its basic parameters to almost all single-stage plants on board diesel engine driven ships [1]. There are three components of the very plant: evaporator, droplets separator or demister and condenser. Moreover, the process of removing the rich solution, namely the brine from the plant and the process of maintaining the necessary vacuum, as plants on board diesel driven ships use waste heat of a relatively low temperature for the evaporating process, should be considered. Two ejectors, that sea water pump is supplying the operational fluid to, have been used in this case. Moreover, it is also important to consider the distillate discharge, that is, the operation and the capacity of the distillate pump, and to monitor its quality and salinity, respectively[1]. The scheme of the simulated plant is shown in Fig. 1.

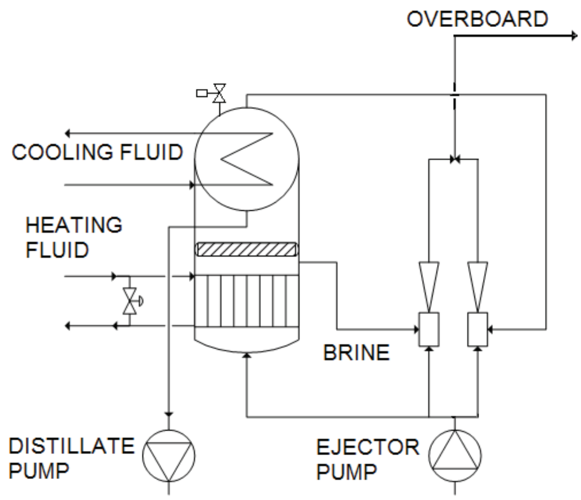

Fig. 1. Fresh water generator [1].

The ejector pump supplies the seawater in a vessel thus generating the operating, propulsive ejector fluid. The rate of the supplied heat is regulated by the by-pass valve, so that at the maximum opened valve the rate is the lowest one, whereas it is the highest when the valve is in its close position. The demister is situated between the heater–evaporator and the condenser. The distillate collected at the bottom of the condenser, in the collecting pan, is discharged by the distillate pump. The brine is discharged by the brine ejector. Since the heating fluid is at a low operating temperature, the plant must operate in the vacuum area ensured by a separate ejector.

The heat exchange processes in the evaporator and the condenser imply the change in the phase. The variable exploitation conditions affect, in both the cases, the heat exchange rate. In the real process, what is changing are the external conditions, some rates within the process that depend on the applied regulation system, the state of the exchanging areas due to corrosion or scale, and so on. The paper implies a constant heat exchange coefficient, as the regulation system of the heating and cooling fluid affects substantially the supply water rate in the evaporator and the discharged heat in the condenser, but at the same time reduces the heat exchange coefficient due to scale [1].

A further simplification of the distillation plant model can be introduced on the assumption that the condenser has a large enough cooling performance, that can be obtained by a large enough exchanging area or by a system regulating the flow of the cooling medium (sea water) through the condenser. Starting from this assumption it follows that the evaporator will be the very dominant factor in the entire operation or capacity of the plant.

Evaporators on modern or evaporators on the already existing plants for the generation of fresh water are designed as vertical ducts[2] around which the heating fluid flows.

[1] Some technological differences are possible. Some plants have only one ejector, while in the other ones, seawater is preheated by passing through the condenser tubes before entering into the evaporator. Low or average pressure plants are used on board ships with a steam turbine propulsion. If large capacities are required, multi-stage plants are installed. These differences do not change the basis of the process.

[2] Older heat exchangers were designed with tubes, while the modern ones are of a plate design, the plate being made of corrugated thin metal sheet. The most recent design of the firm Alfa Laval (Lund, Sweden) has shown heat exchangers and demisters in blocks; blocks are unique and the fluid flows are determined by fitting in rubber gaskets.

Theoretically speaking, evaporation starts at the evaporating duct height at which the saturation pressure and temperature of the seawater are obtained. In practice, the liquid phase must be a little preheated as compared with the saturation temperature, in order to achieve the exchange of substances through the steam bubbles membrane. Furthermore, as compared with the fresh water of the same pressure, seawater, due to a higher surface tension, evaporates at a higher temperature [6,7]. The seawater pressure in the channel depends on the fluid head and on the total pressure in the casing. Depending on the seawater temperature and pressure, the two-phase flow through the vertical channel, operating conditions can appear as shown in Fig. 2[3], and their relation will have an influence on the vertical shift of the first steam bubble place of origin.

The evaporator heat supply rate increase and the increase of the vacuum in the vessel will lead to the evaporating intensity increase and thus resulting in the capacity increase as well, while their decrease will result in a decrease of the capacity. Seemingly, the plant should operate with a vacuum as higher as possible and exploit as larger as possible heat rate. But, that is not how it goes. The influence of the vacuum in the vessel on the condenser efficiency must be kept in mind as must be the influence of the evaporation intensity on the efficiency in dividing brine droplets, namely the obtained distillate salinity [1].

The evaporator and the condenser are installed in the same casing. While, in the case of the evaporator, the higher vacuum in the vessel increases the evaporation intensity, the condensation effect in the condenser decreases. The salt fluid droplets are formed due to the bursting of the steam bubbles at the highest level of the liquid in the evaporator, and are taken off with the gaseous phase to the higher parts of the vessel. The demister should have stopped this, but due to the increased evaporation the number of the droplets grows and their diameter is reduced, so that the function of the demister is of a poor-grade. The result of such an operation will be a distillate of an unsatisfactory quality, that is, increased salinity.

The influence on the process capacity of the plant must be kept in mind, because the total capacity of the plant in a longer period of time has to account the zero capacity period during the repairing works[4] [5–7]. When there is a dry heat exchange by the evaporator wall, that is when the point of appearance of the first steam bubble is too deep in a channel, scale appears more intensively on the evaporator walls. Therefore, although the increase in the evaporating intensity leads to the increase in the current capacity, the process capacity decreases due to often standstills caused by scale cleaning.

Therefore, the plant must be equipped with a regulation system regulating the amount of the heating fluid and the vacuum in the vessel. Assuming that a correct dimensioning and functioning of the gas ejector is in question, the pressure will be too low and the simplest way to regulate this will be by fitting in a valve that will periodically let air into the vessel, while to regulate the heat rate, a regulating by-pass valve will be used, as shown in Fig. 1.

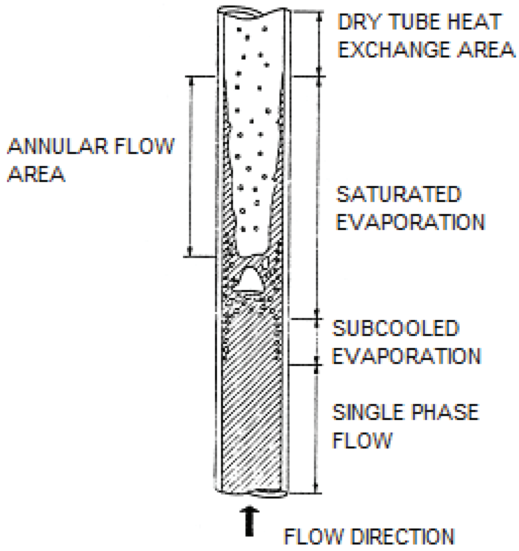

Fig. 2. Vertical channel two-phase flow operating conditions [1,7].

3. The process mathematical model

Accordingly to what has been mentioned above, the fresh water generation process will be substantially affected by: the rate of the supplied and released heat, in which both processes depend on the variable heat exchange coefficients, temperature differences and the flow of two fluids in each of the heat exchangers, pressure in the vessel that influences performances in both heat exchangers as well.

Supposing the maximum flow of the cooling seawater through the condenser and the proper running of the gas ejector[5], the condenser performances will be significantly affected by the temperature differences of the adjacent cooling seawater and the saturation temperature that corresponds to the pressure in the vessel. The temperature difference of the heating fluid flow and of the seawater is an important factor, although not the only one, for the evaporator performances. Qualitative relations of temperatures relating to the relative heat exchanger dimension are shown in Fig. 3.

The seawater temperature at the inlet into the evaporator is almost equal or lower than that of the seawater at the outlet of the condenser. An approximately equal temperature can be obtained if the condenser is used as a preheater of the seawater. For practical purposes, temperatures in the diagram can be considered as determined ones. The highest temperature in the diagram – the heating fluid temperature – is determined by the regulation system and in present-day designs figures out at 80°C, while the lowest temperature

[3] In this case, we speak of a circular cross-section duct or tubular channel.

[4] Under the term repairing works, we understand here long-lasting standstill due to maintenance, replacement of worn out parts and the like, as well as short stoppage of work due to filling in chemicals in order to dissolve scale from evaporator walls.

[5] There are no objective reasons to choke the seawater regulation valve, unless in doing so, the pressure in the pipeline is decreased thus probably causing an unsufficient cooling of the fresh cooling water. The presence of non-condensable gases might decrease the heat exchange coefficient, that, in fact, the ejector eliminates.

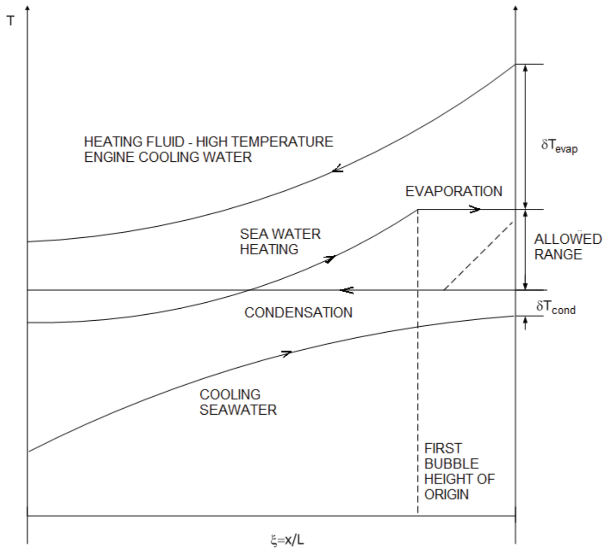

Fig. 3. Qualitative relations of temperatures relating to relative heat exchanger dimensions.

represents the temperature of the adjacent seawater. The seawater temperature values vary on the local basis, but in most cases range from 10°C to 20°C.

The saturation temperature may be determined by the Antoine empirical equation for the known pressure in the vessel and the difference between the condenser and evaporator curves is present due to the increased salt water boiling point[6]. As the temperature differences in the evaporator and the condenser, that is, δT_{evap} and δT_{cond} are, besides the heating and cooling fluid flows, main generators of the heat exchange, what explains how the evaporating intensity will rise and the condensing one will be reduced with the pressure drop in the vessel, and vice versa. It is obvious that an optimum pressure in the vessel can be determined taking into consideration particular external conditions and the conditions of the plant, but due to the system regulating this optimum pressure, a certain range will, as a rule, emerge, within which changes will vary [1].

The energy balance of the plant, as shown in Fig. 3, can be presented by the term as follows:

$$\Delta E = U \tag{1}$$

whereas ΔE represents the difference between the process input and output heat, and U represents the internal energy of the entire plant that can be more precisely defined as:

$$\Delta Q_{\text{heat/HT}} + U_{\text{SW}} - (\Delta Q_{\text{cond}} + U_{\text{brine}} + U_{\text{dist}} + U_{\text{gas}} + Q_{\text{rad}}) = m_{\text{cas}} c_{\text{cas}} \Delta t_{\text{cas}} \tag{2}$$

Parameters stated in Eq. (2) are given in the list of symbols.

As compared with ΔQ_{cond}, U_{brine} and U_{dist}, the two last terms at the left-hand side of Eq. (2) are of a multiply lower order of magnitude and are, as such, negligible. If such simplification could be introduced, then Eq. (2) becomes

$$\Delta Q_{\text{heat\_exch}} + \Delta U_{\text{i/o}} = m_{\text{cas}} c_{\text{cas}} \Delta t_{\text{cas}} \tag{3}$$

where the first term on the left-hand side represents the difference between the heat introduced in the process in the evaporator and the heat removed from the process in the condenser and the second term represents the difference between the inlet sea water internal energy and the output brine and distillate internal energy.

Since the very beginning of the operation, the heat differences have been positive and the casing temperature has risen thus asymptotically approaching the upper limit, while, from the practical point of view, after having achieved the "stationary" state, minor deviations have appeared caused by minor deviations of the external values, characteristics of the control system and so on.

Having in mind that mass and, for the practical purposes, specific heat of casing's material are both constant, the consequence of changes in either of the terms in the left-hand side of Eq. (3) would lead to the change in the temperature of the casing.

4. Simulation of the technological conditions influence

Terms stated at the left-hand side of Eq. (2) are changing depending on the variable external and internal conditions:

- the rate of the heating media is constant at a certain position of the by-pass regulating valve, but the temperature changes in accordance with the changes in the propulsion engine load, with the quality of the system controlling this temperature and with the heat exchange coefficient
- the quantity of the seawater can also be taken as a constant for this type of research, but again the temperature changes with the ship movement
- the quantity of the condenser cooling seawater is constant for the position of the regulating valve, while the heat exchange coefficient changes as well as the seawater inlet temperature, as is the case in the previous section
- the rate of the energy rejected with the brine depends on the first section and on the evaporating intensity
- the rate of the energy released with the distillate depends on the evaporation intensity.

On the plant model that corresponds to the system shown in Fig. 1, key values have been registered. The most important values obtained are shown in Fig. 4.

A six-channel printer has been used. Changes have been reported through a 20-min period of time (from 32 to 52), during which the position of the heating media by-pass regulating valve has been gradually changed in order to increase the evaporation intensity. The figure shows the following values: seawater salinity (constant) in light shade of violet, brine salinity in ochre, obtained distillate salinity in green, quantity of distillate in violet, absolute pressure in the vessel in blue and distillate temperature in black.

A sinusoidal change of almost all dependent values, except inlet sea water salinity, can be seen in the diagram.

[6] In technical English literature, the term "boiling point elevation" is used. It represents the temperature difference between the boiling point of the fresh and salt water of equal pressure and it depends on salinity.

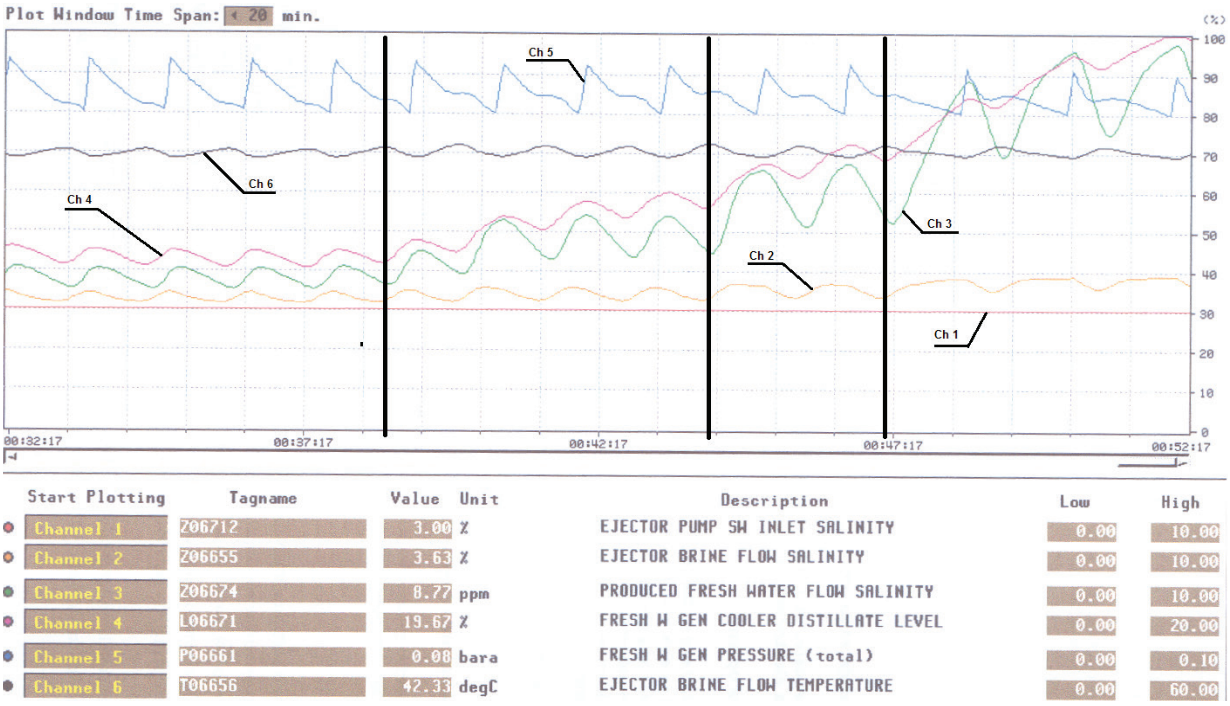

Fig. 4. Registered values on the model [1].

The generator of these changes is the vacuum regulating valve or the vacuum breaker valve adjusted so as to keep a 91%–92% vacuum. The pressure in the vessel varies between 80% and 90%, thus matching the above-mentioned vacuum values. An increase in the quantity of the generated distillate can also be seen and of its salinity as well. Vertical lines mark the moments of the regulating valve position change, that is, the introduction of a larger heating media rate what coincides with the increase in the quantity and salinity of the distillate.

5. Conclusion

Of all the variable values that affect the operation of the plant, by this referring primarily to quantity and quality of the generated distillate, the most important ones are the rate of the heat supplied with the heating fluid and the pressure, namely the vacuum, in the vessel. If a regular operation of the system maintaining the vacuum in the vessel is supposed, its values will oscillate within adjusted, very narrow limits, as will, at the same time, oscillate values of other dependent rates.

It is obvious that a considerable increase in the quantity of the generated distillate can be achieved by increasing the rate of heat supplied with the heating fluid. An unpleasant consequence of such an operation is a lower quality of the distillate, that is, its increased salinity. By using other mathematical models, it should be possible to confirm that, due to a much intensive production of scale on the heating surfaces and due to the need for its more frequent cleaning and removal, the capacity of the plant could be reduced within a longer period of time.

In terms of the energetic analysis of the plant, out of which it can be clearly seen that the plant casing temperature depends on the entire energetic balance, a much simpler and cheaper plant operating system can be installed and an information system developed in order to lead the process in a more efficient way by retaining the necessary characteristics of the produced distillate.

Symbols

c	—	Specific heat capacity, J kg^{-1} K^{-1}
m	—	Mass, kg
ΔQ	—	Heat difference, J
Q	—	Heat, J
Δt	—	Temperature difference, °C
U	—	Internal energy, J

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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

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