Study of the functional parameters of the freshwater generation system, as an integral part of the waste heat recovery system for a tanker ship

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Abstract. A ship needs fuel for both travel and on-board operations. In the most general case, the fuel is converted on board the ship into energy in the form required for its end use: mechanical power for propulsion, electrical power for auxiliary board systems and thermal power for thermal needs. In this paper, I propose to deal with both elements of theoretical calculation and real elements of the operation of the freshwater generation system from the main engine of the ship. I chose to treat this system because it is the main subassembly of the residual heat recovery system from the main engine through cooling water. In the theoretical calculation, the results of the paper will be focus on calculation of the geometric and functional parameters of the fresh water generator. In the final part of the chapter, I will refer to the real parameters of the freshwater generation system where I will draw operation diagrams to highlight as concretely as possible the operation of this system on board the ship.

1. Introduction
Nowadays, the main methods of producing fresh water from sea water are:
- MED -Multiple-effect distillation;
- MSF -Multi stage flash distillation;
- VC-Vapour compression;
- BWRO-Brackish water reverse osmosis;
- SWRO - Sea Water Reverse Osmosis [1].
This paper deals with aspects of theoretical calculation regarding the energy flows of the naval desalination plant. At the same time, emphasis was placed on the real parameters of the desalination plant and real operating graphs were drawn.

Energy consumption for different methods are presented inside the table 1:

Table 1. Energy consumption for different producing fresh water systems.

| Energy type            | MED   | MSF   | VC     | BWRO  | SWRO  |
|------------------------|-------|-------|--------|-------|-------|
| Steam pressure [Mpa]   | 0.02-0.04 | 25-35 |        |       |       |
| Thermal energy [kWh / m³] | 4.5-6  | 9.5-11 |        |       |       |
| Electrical energy [kWh / m³] | 1.2-1.8 | 3.2-4 | 8-12   | 0.3-2.8 | 2.5-4 |
| Total energy [kWh / m³] | 5.7-7.8 | 12.7-15 | 8-12 | 0.3-2.8 | 2.5-4 |

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2. General description of the freshwater generator

The production of fresh water on board is necessary activity for ships with unlimited navigation area and involves its quality in terms of use by various consumers. An important parameter is salt concentration. As a process, distillation takes place with the change of phase, which involves a high energy consumption and is already considered classic. For the reference system, seawater vaporization is performed under vacuum at a temperature $t < 100 \, ^\circ\text{C}$. Main characteristics are shown in table 2 [2].

Table 2. KM 50 characteristics.

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|
| 1          | Type                                                 | KM 50                              |
| 2          | Capacity                                             | 40 tones / day                     |
| 3          | Heat consumption                                    | 1140.5 kW                          |
| 4          | Sea water cooling inlet temperature                  | 32 °C                              |
| 5          | Sea water cooling outlet temperature                 | 40.3 °C                            |
| 6          | Sea water flow                                       | 115 m$^3$/h                       |
| 7          | Maximum pressure losing                              | 0.0343 MPa                         |

**Cooling sea water**

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|
| 8          | Cooling water from the main engine to fresh water generator inlet | 75 °C                            |
| 9          | Cooling water from the main engine to fresh water generator outlet | 62.1 °C                            |
| 10         | Cooling water flow                                   | 76 m$^3$/h                        |
| 11         | Maximum pressure losing                              | 0.0294 MPa                         |

**Sea water cooling from main engine**

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|
| 12         | Condenser pressure                                   | 0.38 MPa                           |
| 13         | Heat exchanger - heater                               | 0.44 MPa                           |
| 14         | Heat exchanger - vaporizer                            | 0.10 MPa                           |

**Other components**

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|
| 15         | Flow                                                 | 2.5 m$^3$/h                        |
| 16         | Head                                                 | 0.36 MPa                           |
| 17         | Power                                                | 1.5 kW                             |

**Distillate pump**

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|
| 18         | Flow                                                 | 36 m$^3$/h                         |
| 19         | Head                                                 | 0.38 MPa                           |
| 20         | Power                                                | 7.5 kW                             |

**Ejector pump**

| Current no. | Characteristics                                      | Value                              |
|------------|------------------------------------------------------|------------------------------------|

Figure 1. Fresh water generator SASAKURA KM50 [Horaisan tanker ship].
The reference desalination plant is shown in figure 1. Once it has reached boiling temperature, it is at a lower pressure than atmospheric pressure, salt water goes through a partial stage of evaporation and generates a mixture of steam and salt. The brine is separated from the steam and extracted by means of the combined air / brine ejector [3].

The vessels pass through the separation zone and enter the second plate channel (each channel being composed of plates) from the condensation section. Cooling water is distributed through the other channel and absorbs heat which is transferred by the steam from the condensing zone. Finally, the fresh water generated is extracted by means of the water pump and pumped to the fresh water tank [4].

3. Calculation of theoretical energy flows on the freshwater generator

The saturation temperature can be determined by the Antoine empirical equation for the known pressure in the vessel and the difference between condenser and evaporator. The curves are present depending on the boiling point of the salt water. Because the temperature differences between the evaporator and the condenser (adică δT_{evap} și δT_{cond}) are in addition to heating and coolant flows, the main generators of heat exchange, which explains how the vaporisation intensity will increase and condensation will be reduced with the fall pressure in the vessel and vice versa.

It is obvious that an optimal pressure in the vessel can be determined, taking into account, in particular, the external conditions and the conditions of the distiller, but due to the optimal pressure regulation system, a certain interval will appear, usually within which the changes will vary [5].

The energy balance of the distiller (as shown in figure 2), can be presented in terms as follows:

\[ \Delta E = U \]

where \( \Delta E [\text{kJ}] \) represents the difference between the inlet and outlet heat process, and \( U [\text{kJ}] \) represents the internal energy of the whole distiller which can be defined more precisely as:

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

(2)

If we compare \( \Delta Q_{\text{cond}}, U_{\text{brine}} \) and \( U_{\text{dist}} \), the last two terms to the left of the equation are negligible. The equation will become:

\[ \Delta Q_{\text{heat/each}} + U_{\text{in/out}} = m_{\text{cas}}c_{\text{cas}}\Delta t_{\text{cas}} [\text{kJ}] \]

(3)

where the first term on the left represents the difference between the heat introduced into the evaporator exchange process and the heat removed from the condenser exchange process; the second term represents the difference between the internal energy of the inlet seawater and the outlet energy of the brine and distilled water. From the beginning of the exchange process, the differences in heat were positive [6].
Figure 2 shows the operation of the naval distiller through the electronic command and control program. The light blue part represents the energy flow from the main engine and has an inlet temperature of 80 °C and has the role of heating (vaporisation). The green part represents the energy flow from seawater and has the role of cooling (condensation). The condensation temperature is 20 °C. The dark blue colour is the distillate from vaporization and condensation. The higher the quantity of distillate, the lower the quality (higher salinity) and, conversely, the lower the amount of distillate, the higher the quality (lower salinity). At the same time, we have a pink brine that is evacuated with the help of an ejector that works with sea water. Also, the energy flows for auxiliary systems are shown in figure 3 [7].

Figure 3. Energy flow [8].
The thermal flow of sea water cooling

Seawater has been used for long time as a cooling fluid in heat exchangers to reduce fresh water usage in industry and power plants.

The sea water pump flow is:

\[ \dot{V}_{cool} = \frac{115}{3600} = 0.0319 \frac{m^3}{s} \]

The specific heat is:

\[ c_{sw} = 4.19 \frac{KJ}{KgK} \]

The inlet temperature of sea water is:

\[ t_{in} = 32^\circ C \]

The outlet temperature of sea water is:

\[ t_{out} = 40.3^\circ C \]

The sea water density is:

\[ \rho_{SW} = \frac{1025 Kg}{m^3} \]

The energy flow of cooling sea water is:

\[ \dot{Q}_{cool} = \dot{V}_{cool} \cdot \rho_{sw} \cdot c_{sw} \cdot (t_{out} - t_{in}) = 1137.12 \text{ [kW]} \]  \hspace{1cm} (4)

Energy flow of cooling water from main engine

The fresh water pump flow is:

\[ \dot{V}_{fw} = \frac{76}{3600} = 0.0211 \frac{m^3}{s} \]

The Specific heat is:

\[ c_{fw} = 4.19 \frac{KJ}{KgK} \]

The inlet temperature of fresh water is:

\[ t_{in} = 75^\circ C \]
The outlet temperature of fresh water is:
\[ t_{out} = 62.1^\circ C \]

The water density is:
\[ \rho_{fw} = 1000 \frac{Kg}{m^3} \]

The energy flow of cooling fresh water is:
\[ \dot{Q}_{fw} = \dot{V}_{fw} \cdot \rho_{fw} \cdot c_{fw} \cdot (t_{out} - t_{in}) = 1140.47 \text{ [kW]} \] (5)

4. Calculation of real energy flows on the freshwater generator
For calculation will use 4 and 5 formulas.

Energy flow of sea water
\[ \dot{Q}_{cool} = \dot{V}_{cool} \cdot \rho_{sw} \cdot c_{sw} \cdot (t_{out} - t_{in}) \text{ [kW]} \] (6)

Energy flow of fresh water
\[ \dot{Q}_{fw} = \dot{V}_{fw} \cdot \rho_{fw} \cdot c_{fw} \cdot (t_{out} - t_{in}) \text{ [kW]} \] (7)

In table 3 the actual energy flows were calculated according to the flow rates and temperatures of the working fluids using equations (6) and (7).

**Table 3.** Real energy flows in fresh water generator.

| Crt. no. | Fresh water flow [m³/day] | Cooling water flow [m³/day] | Cooling water flow [m³/h] | Energy flow [kW] | Maximum energy flow [kW] | Water flow main engine [m³/h] | Water energy flow main engine [kW] | Maximum energy theoretical flow sea water main engine [kW] | Sea water temp [°C] | Water temp main engine [°C] |
|----------|---------------------------|----------------------------|----------------------------|-----------------|--------------------------|----------------------------|-------------------------------|--------------------------------|-------------------|--------------------------|
| 1        | 33                        | 94.9                       | 0.026                      | 1358.2          | 1137.1                   | 62.7                       | 0.017                         | 1313.6                         | 1140.5             | 32                       | 44                       | 78                       | 60                       |
| 2        | 32                        | 92.0                       | 0.026                      | 1207.3          | 1137.1                   | 60.8                       | 0.017                         | 1273.8                         | 1140.5             | 31                       | 42                       | 78                       | 60                       |
| 3        | 31                        | 60.4                       | 0.017                      | 720.3           | 1137.1                   | 39.9                       | 0.011                         | 928.8                          | 1140.5             | 28                       | 38                       | 78                       | 58                       |
| 4        | 29                        | 83.4                       | 0.023                      | 1094.1          | 1137.1                   | 55.1                       | 0.015                         | 1154.3                         | 1140.5             | 26                       | 37                       | 75                       | 57                       |
| 5        | 31                        | 89.1                       | 0.025                      | 1063.2          | 1137.1                   | 58.9                       | 0.016                         | 1234.0                         | 1140.5             | 30                       | 40                       | 75                       | 57                       |
| 6        | 33                        | 94.9                       | 0.026                      | 1131.8          | 1137.1                   | 62.7                       | 0.017                         | 1167.6                         | 1140.5             | 31                       | 41                       | 73                       | 57                       |
| 7        | 31                        | 89.1                       | 0.025                      | 1063.2          | 1137.1                   | 58.9                       | 0.016                         | 1165.4                         | 1140.5             | 32                       | 42                       | 76                       | 59                       |
| 8        | 34                        | 97.8                       | 0.027                      | 1282.8          | 1137.1                   | 64.6                       | 0.018                         | 1353.4                         | 1140.5             | 32                       | 43                       | 78                       | 60                       |
| 9        | 36                        | 103.5                      | 0.029                      | 1358.2          | 1137.1                   | 68.4                       | 0.019                         | 1273.8                         | 1140.5             | 32                       | 43                       | 76                       | 60                       |
| 10       | 36                        | 103.5                      | 0.029                      | 1358.2          | 1137.1                   | 68.4                       | 0.019                         | 1273.8                         | 1140.5             | 32                       | 43                       | 76                       | 60                       |
| 11       | 39                        | 54.6                       | 0.015                      | 521.3           | 1137.1                   | 36.1                       | 0.010                         | 798.3                          | 1140.5             | 32                       | 40                       | 76                       | 57                       |
| 12       | 25                        | 71.9                       | 0.020                      | 1286.2          | 1137.1                   | 47.5                       | 0.013                         | 718.7                          | 1140.5             | 31                       | 46                       | 76                       | 63                       |
| 13       | 36                        | 103.5                      | 0.029                      | 1282.8          | 1137.1                   | 68.4                       | 0.019                         | 1034.9                         | 1140.5             | 31                       | 45                       | 76                       | 63                       |
| 14       | 38                        | 109.3                      | 0.030                      | 1955.0          | 1137.1                   | 72.2                       | 0.020                         | 1092.4                         | 1140.5             | 30                       | 45                       | 76                       | 63                       |
| 15       | 36                        | 103.5                      | 0.029                      | 1358.2          | 1137.1                   | 68.4                       | 0.019                         | 955.3                          | 1140.5             | 29                       | 40                       | 76                       | 64                       |
| 16       | 28                        | 80.5                       | 0.022                      | 1056.4          | 1137.1                   | 53.2                       | 0.015                         | 1176.5                         | 1140.5             | 29                       | 40                       | 76                       | 57                       |
| 17       | 27                        | 77.6                       | 0.022                      | 1018.7          | 1137.1                   | 51.3                       | 0.014                         | 1134.4                         | 1140.5             | 31                       | 42                       | 76                       | 57                       |

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Figure 4. Sea water energy (blue). Fresh water energy (red) – kW.

In figure 4 the energy flows for technical water as well as for salt water. At the same time, the graph provides a comparative image between the second flow with values in kW [9].

Figure 5. Sea water energy (blue). Water cooling theoretical energy flow (red) in kW.

In figure 5 the energy flow from sea water is compared to the maximum theoretical flow calculated. Several peaks can be observed that exceed the maximum theoretical flow, this does not significantly influence the condensation [10].
Figure 6. Fresh water energy (red). Water cooling theoretical energy flow in the main engine (blue) in kW.

In figure 6 the energy flow from the main engine is compared to the calculated maximum theoretical flow. Several peaks can be observed that exceed the maximum theoretical flow. Most of the time the engine is running below the maximum value of the flow from its cooling water.

5. Conclusions
The terms in the energy flow equations change depending on the external and internal variable conditions:
- the average rate of heating flow is constant at a certain position of the by-pass control valve, but the temperature changes according to the load changes of the propulsion engine, with the quality of the system controlling this temperature and with the heat exchange coefficient.
- the amount of condensing cooling seawater is constant for the position of the control valve, while the heat exchange coefficient changes with the seawater temperature at the inlet.
- the rate of energy lost with brine depends on the intensity of evaporation.
- the rate of energy released suitable with the distillate also depends on the intensity of evaporation.

Of all the values of the variable energy flows that determine the operation of the distiller, referring primarily to the quantity and quality of the distillate generated, the most important are the rate of heat supplied by the heating fluid and the working pressure (vacuum) [11].

A considerable increase in the amount of 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, ie its increased salinity.

The heat from the main engine through its cooling fluid is the deciding factor in the quality and quantity of distillate produced.

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