Corrosion and Material Selection for Desalination Plant Heat Exchangers

Ghenai C.

Ocean and Mechanical Engineering Department, College of Engineering and Computer Science, Florida Atlantic University, Boca Raton, FL, USA

Abstract:
The principle objective of this study is to select the best material for sea water cooled heat exchanger used in desalination plant. A list of design requirements (objectives, constraints) the heat exchangers material must meet has been developed. The selection tools form the Cambridge engineering selector software has been used during the screening process. The selected materials have been ranked based on the objectives (maximize the heat flux and minimize the price). The results show that the stainless steel duplex is the best material for the condenser. It has a high thermal conductivity and yield strength, excellent resistance of the material to sea water, and withstands corrosion (very good resistance of the material to pitting and crevice corrosion and excellent resistance to stress corrosion cracking). The stainless steel duplex has very a low cost ($/Kg), low embodied energy (J/kg) and low CO2 emissions (carbon foot print) during the primary material production.

Keywords: Thermal Desalination, MSF, Condenser, Corrosion, Material Selection

1. INTRODUCTION

Desalination of seawater is one of the most promising techniques used to overcome water shortage problems [1]. The desalination techniques include thermal desalination processes (Multi Stage Flash - MSF, Multi Effect Distillation – MED) and membrane desalination processes (reverse osmosis – RO and Electro-Dialysis Reverse -EDR). Multi Stage Flash (MSF) is one of he most commonly distillation process used for large-scale desalination of seawater [2]. In the MSF process, the seawater enters the evaporation chamber resulting in flash boiling of a fraction of the seawater. The vapour produced by flashing is then conveyed to the heat recovery section where it is condensed. Heat exchanger (evaporator and condensers) tubes represent the largest item in an MSF plant and not surprisingly more than 70% of the corrosion failures in desalination plants are attributed to heat exchange tubes. Heat exchangers tubes handle two fluids of completely different properties (seawater and vapors). It is one of the severest environments from the point of view of corrosion [3-4]. This study focuses only on the desalination plant condensers. The condenser is a sea water-cooled shell and tube heat exchanger installed in the exhaust steam from the evaporator in thermal
desalination plant. The condenser is a heat exchanger that converts the steam received from the evaporator to liquid using the sea water as the cooling fluid. The key properties of the desalination plant surface condenser are: (1) heat transfer properties (thermal conductivity, convective heat transfer coefficients for steam and sea water, and fouling coefficients); (2) the erosion resistance (to steam for the external surface of the tube, and to raw sea waters which may contain sand and show turbulences for the internal surface of the tube); (3) corrosion resistance (to raw sea waters, steam and condensate). The heat transfer performance of the condenser is linked to the material selection - thermal conductivity, thickness, and the erosion/corrosion resistance of the tubing materials. A condenser with high tubing thermal conductivity, thin wall tubing, and tubing surface that do not corrode in the heat exchanger environment and remains relatively clean during the desalination process will provide excellent heat transfer performance. The principal objective of this study is to select the best materials for the condenser tubing that will provide excellent thermal heat transfer performance.

2. METHODOLOGY

2.1 Heat Transfer Model and Performance Index for the Condenser:

The condenser takes heat from the steam and passes it to the sea cooling water. The steam enters the shell at temperature $T_V$, changes its phase from gas to liquid during the heat transfer with the sea cooling water and exit the heat exchanger as condensate at temperature $T_C$. The sea water cooling fluid enters the condenser tubes at temperature $T_{CW}$ and exit at high temperature $T_{HW}$. A key element in all heat exchangers is the tube wall or membrane which separates the sea water and the steam. It is required to transmit heat and there is frequently a pressure difference across it $\Delta p$ (pressure difference between the sea water and the steam pressures). The question is what are the best materials for making these condensers? What are the best condenser materials that can provide high thermal conductivity but at the same time can sustain this pressure difference? What is the performance index that can be used for heat exchanger or condensers? The heat transfer from the steam to the sea water through the membrane or the thin wall involves convective transfer from steam to outside surface of the condenser tubes, conduction through the tube wall, and convection again to transfer the heat to sea water. The heat flux $q$ into the tube wall by convection (W/m$^2$) is described by the heat transfer equation $q = h_1 \Delta T_1$, where $h_1$ is the heat transfer coefficient for the steam and $\Delta T_1$ is the temperature drop across the surface from the steam into the outside tube wall. Conduction is described by the conduction equation: $q = (\lambda \Delta T_{12})/e$, where $\lambda$ is the thermal conductivity of the wall (thickness $e$) and $\Delta T_{12}$ is the temperature difference across the tube wall. The heat flux $q$ out from the tube wall by convection is described by the heat transfer equation $q = h_2 \Delta T_2$, where $h_2$ is the heat transfer coefficient for sea water and $\Delta T_2$ is the temperature drop from the inside surface of the tube to the sea water. The heat flux is also given by: $q = U (T_V - T_{CW})$, where $U$ is the overall heat transfer coefficient and $T_V$ is the steam temperature entering the shell and $T_{CW}$ is the temperature of sea water entering the tube. The overall heat transfer coefficient is
The total heat flow is
\[
Q = q \ A = \left( \frac{1}{h_1 + \frac{e}{\lambda} + \frac{1}{h_2}} \right) \ A \ (T_v - T_{cw}).
\]

One of the constraints of the heat exchanger is that the wall thickness must be sufficient to support the pressure difference \( \Delta p \). This requires that the stress in the wall remain below the elastic limit (yield strength): \( \sigma = \frac{\Delta p \ r}{e} \left( \sigma_{el} \right) \). The heat flux is given by:
\[
\frac{Q}{A} = q = \left( \frac{1}{h_1 + \frac{\Delta p \ r}{\lambda \sigma_{el} + h_2}} \right) \ (T_v - T_{cw}).
\]

The heat flow per unit area of tube wall, \( Q/A \) or \( q \) is maximized by maximizing the performance index \( M \) given by \( M = \lambda \sigma_{el} \). The maximum value of \( M \) is obtained by minimizing the tube wall thickness or maximizing both the thermal conductivity and the yield strength.

### 2.2. Strategy for Material selection:

Selecting materials for the condenser involves seeking the best match between design requirements and the properties of the materials that may be used to make the heat exchanger. The strategy for selecting the material for desalination plant heat exchangers is:

(a) Translate design requirements: develop a list of requirements the material must meet, expressed as function (what does the system do), objectives (what is to be maximized or minimized), constraints (what nonnegotiable conditions must met) and free variables (what parameters of the problem is the designer free to change). The main function of the condenser is to exchange heat between the steam and seat water (heat exchanger) and to convert the steam to distilled water. The objectives are to maximize heat flow per unit area and minimize the cost. The constraints for the condenser are: (a) operating temperature up to 150\(^\circ\)C; (b) support pressure difference \( \Delta p \), (c) excellent resistance to sea water, (d) very high resistance of the material to pitting and crevice corrosion, and (e) excellent resistance of the material stress corrosion cracking. The free choices for the condenser design are the choice of material.

(b) Screening: After developing the list of requirements the material must meet, the next step is to eliminate the materials that can not do the job because one or more their attributes lies outside the limits set by the constraints. The limit and tree stages of the Cambridge selector software from Granta Design are used in this study as selection tools for the screening process. The limit stage applies numeric and discrete constraint. Required lower or upper limits for material properties are entered into the limit stage property boxes. If a constraint is entered in the minimum box, only materials with values greater than the constraint are retained. If it is entered in the Maximum box, only materials with smaller values are retained. The graph option can be used to create bar charts and bubble charts. A box selection isolates a chosen part of a chart. Any material bar or bubble lying in, or overlapping the box is selected and all others are rejected. The line selection divides a
bubble chart into two regions. The user is free to choose the slope of the line, and to select the side on which materials are to be chosen. This allows selection of materials with given values of combinations of material properties such as $E/\rho$, where $E$ is Young’s modulus and $\rho$ is density. The tree stage allows the search to be limited to either: a subset of materials (metals, hybrids, polymers, and ceramics) or materials that can be processes in chosen ways (manufacturing process).

(c) Ranking: Find the screening materials that do the job best. Rank the materials that survive the screening using the criteria of excellence or the objectives and make the final materials choice.

3. RESULTS AND DISCUSSION

![Figure 1 Results of the Screening Process – Performance Index M versus Material Cost](image1)

![Figure 2 Results of the Screening Process – Embodied Energy versus the CO2 footprint](image2)
Table 1. Selected Materials for the desalination plant condenser based on the materials ranking or the design objectives (high heat flux or performance design M and low cost)

<table>
<thead>
<tr>
<th>Material</th>
<th>Performance Design $M = \hat{\lambda} \sigma_{el}$</th>
<th>Price $$/Kg$</th>
<th>Pitting and Crevice Corrosion</th>
<th>Stress Corrosion Cracking</th>
<th>Embodied Energy $$(J/Kg)$$</th>
<th>Maximum Service Temperature $$(C)$$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stainless Steel, Duplex</td>
<td>$7.3e9 - 9.4e9$</td>
<td>$13.2 - 15.2$</td>
<td>Very High</td>
<td>Excellent</td>
<td>$7.7e7 - 8.5e7$</td>
<td>$335 - 365$</td>
</tr>
<tr>
<td>UNS S32550, wrought</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Stainless Steel, Duplex</td>
<td>$6.9e9 - 8.1e9$</td>
<td>$14.2 - 15.7$</td>
<td>Very High</td>
<td>Excellent</td>
<td>$7.7e7 - 8.5e7$</td>
<td>$335 - 365$</td>
</tr>
<tr>
<td>UNS S32760, wrought</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. CONCLUSION

A material selection strategy for desalination plant condenser is presented in this paper. The strategy is based on (1) the translation of the design requirements: development of a list of requirements expressed as constraints (maximum service temperature $> 150C$; excellent resistance to sea water; very good resistance to pitting and crevice corrosion; and excellent resistance to stress corrosion cracking) and objectives (maximize the heat flux and minimize the cost); (2) Engineering selector software selection tools to eliminate the materials that can not do the job; and (3) ranking the selected materials based on the objectives. The results of the selection process show that the best material that can be used for the desalination plant condenser is the stainless steel, duplex UNS S322550, wrought. This material has (1) the highest design performance $M$ (high heat flux), (2) the lowest cost ($13 - 15 $$/Kg$), (3) a very good resistance to pitting and crevice resistance, (4) an excellent resistance to stress corrosion cracking (no breaks at high strengths or $> 75\%$ of yield strength in various environments), (5) excellent material resistance to sea water (no degradation in material performance expected after a long exposure to sea water), and (6) a good pitting resistance equivalent number (PREN = 40). In addition the embodied energy (energy required to make 1 Kg of the material) and the CO2 footprint (mass of CO2 released during the production of 1 Kg of the material) are very low compared to the other materials.

5. REFERENCES


