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Optimization of seawater evaporation plants

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Abstract

For the majority of power plants located at the sea, the boiler make-up water is produced by thermally driven desalination plants. The cost of distillate produced by evaporation is influenced both by capital investment and by the running costs of the plant. There is a trade-off between capital investment and operational cost whereby the higher the investment cost, the more efficient the operation of the plant. This in turn reduces the running cost, mainly by reducing specific power consumption. SWS has developed an accurate optimization program which finds the most convenient balance between plant efficiency directly proportional to capital investment and running costs. The program operates for any required return on an investment from 1 to 7 years. The optimal point is, of course, influenced by market factors such as the price of energy (electrical, steam, fuel) and by applicable interest for the amortization of the investments. Therefore, the optimization is to be suited for the specific conditions for each project. The findings, however, are that significant savings can be achieved at any site or conditions through the proper identification and specification of the most convenient plant.

Keywords: ???

1. Introduction

The technology of motor vapour compression (MVC) desalination is quite widely used, and several plants have been operating successfully worldwide for decades. The present state-of-the-art enables the designer of the plants to select well-tested materials from the following:

- shell: lined carbon steel (epoxy-glass flakes), SS 316 L or duplex steel
- tubes: titanium (typically B 338 Gr. 2), Al alloy (typically 5052), Al brass (typically UNC C 68700)

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The selection of the materials has a great influence on the construction cost and on the life expectancy of the plant, which is also to be considered in respect of the expected return on the investment (ROI). Moreover, the designer of the plant can select the working conditions of the multi-effect desalination plant choosing within a wide range of pressure differences (ΔP) across the compressor between the vapour recirculated to the first stage, according to the requested differential temperature (ΔT) available in the condensation/evaporation process. This selection significantly influences the extension of the necessary heat transfer surface as to be evaluated according to the materials selected. The selection of the working ΔT also has an impact on the energy consumption of the plant. The larger the ΔT, the smaller (and more economical) the evaporator. The impact on the running costs is to be evaluated according to the cost of the kW/h in the country and market situation of the plant.

2. Scope of the study

The scope of this study is the optimization of the working ΔT for the minimization of the cost of the distillate, as a function of: (1) requested return of the investment, (2) cost of the energy (running costs), and (3) cost of manufacturing (investment cost), also influenced by the materials selected.

The analysis of the result provides a reliable guideline to end-users and manufacturers for the assessment of the most convenient design conditions of the plant.

3. Optimization philosophy

There are several different approaches in the design phase for the design criteria to be adopted to achieve a given production capacity as follows: (1) with a larger installed exchanging surface (higher investment cost) and a smaller working ΔT (lower energy demand), or (2) with a smaller installed exchanging surface (lower investment cost) and a larger working ΔT (higher energy demand). All the efforts of designers and producers of desalination plants are aimed at reducing investment costs by increasing the working ΔT up to the maximum extent achieved by the VC technology. The producers of compressors, therefore, have maximized the design of the impellers up to and over 6°C of (saturated) ΔT (that is the maximum achievable for the present state-of-the-art in vapour compressors).

The relevant working conditions, however, force the operator to spend up to 50% more for electricity than under smoother working conditions. Therefore, the optimized balance between investment costs and running costs should be considered and determined for each specific project, as a function of the following parameters:

- Service mode (discontinuous, continuous, heavy duty)
- Return on the investment (1 year, many years)
- Cost of electricity, €/kWh
- Specific construction costs (low-grade materials or high-grade materials)
- Applicable interest rates

4. Cases

The engineers of SWS are now involved in three different projects with very different conditions, sites of installation, capacity and optimization criteria. For each project, the client established different optimization parameters that led to different arrangements of the plant. Accordingly, an optimization was assessed.

For this the engineers of SWS studied and tested an optimized procedure for the determination of the most convenient arrangement of the plant, according to the parameters listed. The optimization procedure focused on the ΔT per effect, and a range of 2 to 7°C was explored accordingly (see Table 1).

Table 1
Optimization assessment

Client	Location	Capacity, t/h	Status	Service	Design criteria	Tube materials	Optimized arrangement
Government of India	Mumbay	2.1	In progress	Discontinuous	Minimization of electricity consumption	Titanium[a]	Two effects Total ΔT = 5°C (2.5˚C/effect)
EDF France	Guadalupe	10	In progress	Continuous	Minimization of investment cost	Titanium	Single effects Total ΔT = 5.5°C (5.5˚C/effect)
ENI Italy	Taranto	120	In bid evaluation (TVC alternative is considered)	Heavy duty	Optimization of investment and running costs in 7 years	Alloy 5052	Three effects Total ΔT = 11˚C (3.7°C/effect) (Note: ΔT = 11°C achieved by two impellers in serial arrangement)

[a]Note: one spare set of Al 5052 tubes shall be installed for test purpose.

5. Calculation method

During the design phase of a new desalination plant (i.e., MVC, MED) or when upgrading an existing facility, different process alternatives and operating strategies could be evaluated by calculating a cost index using commercially available software packages. However, actual cost indices are often restrictive since only investment or specific operating costs are considered.

Moreover, all process and project engineering contractors active in the field of desalination are proposing new contracts based on the repayment period concept, for which the total desalination plant cost,, i.e. investment cost + fixed and variable operating cost, is of utmost importance. Therefore, SWS started an ambitious R&D project aiming at the development of a new software tool (SWSOPTIMO) for the purpose of an economic evaluation of a desalination plant over its repayment period.

5.1. Desalination plant cost index

Within SWSOPTIMO, an objective cost index should integrate the investment cost as well as fixed and variable operating costs. The latter are usually not taken into account in commercially available software tools or optimization studies according to the literature.

In order to assess the preliminary costs of a desalination plant — to be able to choose between different alternatives in the early phase of a process design — cost functions may be used. Therefore, investment and operating cost functions are presented in the sequel, which may guide the development of a systematic cost calculation procedure.

5.2. Investment cost functions

Investment costs for major treatment plant units may be quantified as a function of the process size (e.g., volume, area, flow rate) by use of power laws or polynomial functions. To estimate investment costs related to piping or electrical works, cost factors (percentage of the investment cost) are often applied. An example of investment cost function for a MVC is:

$$IC = f(\Delta t) = \frac{K}{g(\Delta t)} * M = \left(\frac{€}{\text{ton/h}}\right)$$

$$K = \left(\frac{m^2 * °C}{ton/h} \right)$$

$$M = (€ / m^2)$$

On the basis of functions presented, the investment cost of a desalination plant may be calculated as an hyperbolic curve depending on the design parameter (Δt). Cost functions are indeed developed at a given time for a specific company, region or country and any extrapolation is not without risk. Moreover, it is difficult to compare various relationships extracted from different sources, as the description of the components taken into account in the relationships is often poor, and an indication of the accuracy obtained using literature data is rarely provided. As a result, cost analysis in the early phase of a process design requires the development of specific cost functions to obtain an accurate and reliable cost estimation.

5.3. Operating cost functions

The total operating cost of a desalination plant may be related to global plant parameters (e.g., average flow rate), generally through power laws. However, such relationships apply to the average performance of plants and often suffer from a high uncertainty unless very similar plant configurations are considered.

In order to take into account dynamic simulation data to estimate operating costs, deductive models may be issued from engineering calculations. However, such development requires some skill, and on-site data collection is preferable when possible (e.g., for an upgrade of an existing plant), in order to check and refine existing cost models or to build new (inductive) models on the basis of collected data. Table 2 compiles different cost functions that may be used to estimate operating costs.

Table 2
Examples of operating cost functions

Cost item	Formula	Reference
Normal operation and maintenance	$L = Uc\ PE$	Jacquet, 1999
Pumping power	$P = Qwh / \eta$	ASCE, 1992
Small equipment (supplies, spare parts)	$C = Uc.\ PE$	Alexandre & Grand d'Esnon, 1998
Analysis	$C = Uc.\ PE$	″

Cost functions given in Table 2 only illustrate possible models in their generic form. As seen in Table 2, fixed operating costs may be related to the plant size or unit size (PE, volume, area). Finally, when comparing different alternatives, special attention should be paid to the time and space scales chosen as they may influence the choice of the implemented cost functions. At best, an overall plant evaluation over the life span of the plant should be conducted.

5.4. Total cost of a desalination plant

The total cost of a plant is usually determined using the present worth method. All annual operating costs for each process are converted into their corresponding present value and added to the investment cost of each process to yield the net present value (NPV). When IC_k represents the investment cost of a unit k and OC_k the operating cost, the net present value of a plant over a period of n years can be determined as:

$$NPV = \sum_{k=1}^{N} IC_k + \left[\frac{1-(1+i)^n}{i} \right] \sum_{k=1}^{N} OC_k$$

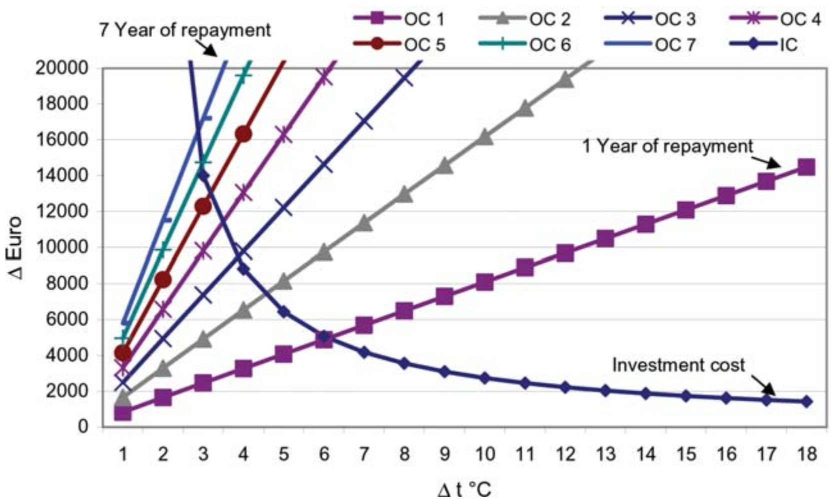

Fig. 1. Cost curves (1 m^3/h production rate).

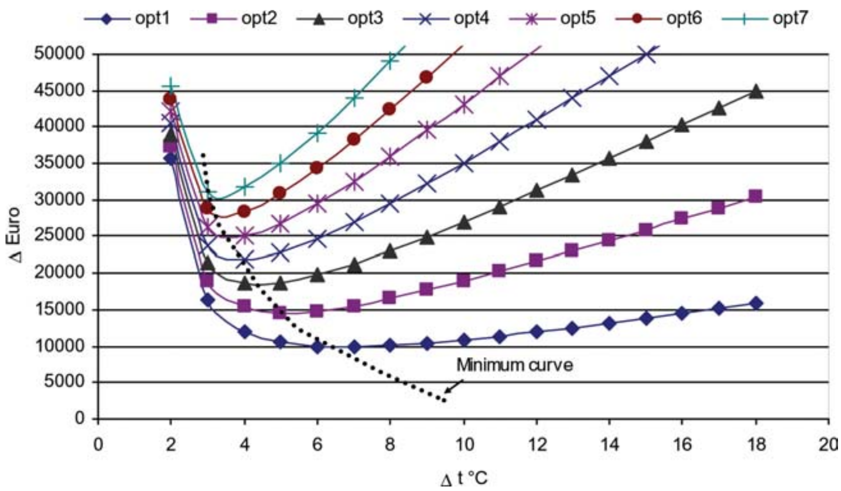

Fig. 2. Optimization curves (1 m^3/h production rate).

where i is the interest rate and N is the number of units.

On the basis of functions presented in Table 2, an overall cost index may be formulated as the NPV. The optimization curves, each for every year of repayment, can be determined as result of the minimum of each NPV curve.

5.5. Application (Figs. 1 and 2)

Plant type:	MVC
Tubes:	Titanium
Years of repayment:	7
Shell:	316 L
Energy cost:	0.046 €/kWh
Delta fabrication cost:	98 €/m^2 exch. surf.
Costs:	evaluated at 1 m^3/h of production

6. Results

The longer the considered ROI, the lower the ΔT as appropriate to reduce the running cost. However, reducing ΔT below 2.5˚C does not provide any further advantage because of the very sharp excess of investment costs. For short ROI (1 or 2 years) the optimized point of operation does not provide remarkable advantages against any other point of design. For long ROI (6 or 7 years) the optimized point of operation provides considerable advantages according to the selected design working conditions. The optimized point corresponds to a lower ΔT than usually proposed by the designers of the plants or requested by the end-users. An optimized ΔT of 3.5÷3.8°C reduced the cost of distillate in the return period quite remarkably.

7. Conclusions

Most of the plants delivered to various clients worldwide are not actually optimized. The requested ROI should be assessed by the client and disclosed to the designer before the issue of the specifications of the plant. From these data adequate construction materials can be selected according to the ROI, and optimized thermodynamic working conditions can be referred to for the most economical production of distillate water. The reduction of the cost of water can be surprisingly high to the benefit of the client's budget. The general guideline is the following:

	Short ROI	Long ROI
Materials	Low grade	High grade
ΔT	As high as possible	Limited within 2.5÷4°C

For each specific project, the most convenient ΔT can be calculated and the plant optimized accordingly. The longer is the requested ROI, the more important it is to assess the actual optimized ΔT as a function of the other parameters such as interest rates, construction cost and energy costs (specifically calculated for the country of destination of the plant).

8. Symbols

C	—	Cost, €/y
h	—	Dynamic head, m
i	—	Interest rate
L	—	Labor, man-hour/y
N	—	Number of units
P	—	Power, kW
ΔP	—	Pressure
PE	—	Population equivalent
Q	—	Flow rate, m^3/s
ΔT	—	Temperature, C
Uc	—	Unit cost, €/y
w	—	Specific liquid weight, N/m^3
η	—	Pump efficiency