

Study on Economics of the Salt Manufacturing Processes Employed in Japan

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ABSTRACT

The salt manufacturing process in Japan is composed of three sub-processes, production of brine by concentrating seawater, crystallization of salt by evaporating the brine, and utilities which supply energy in the required forms. The utility process is an important sub-process for salt manufacture, as it virtually determines the economics of the entire process. Since 1950 various industrial technologies have been employed in Japan for each sub-process.

All the salt production processes discussed in this paper are combinations of the above sub-processes and the study was conducted first on each sub-process and then on their combinations and cost analyses in terms of energy. In this paper, electric power and steam energy required for each sub-process are converted into an unified unit of "exergy" (Rant, 1956). It corresponds to energy cost only when the cost and efficiency of converting fuel energy to electric power and steam are taken into account. This method is most suitable for selecting the best combination of sub-processes as it makes it possible to obtain the theoretical and actual energy requirements of each salt manufacturing sub-process separately as well as their cost and efficiency of their utility sub-process.

The study led to the conclusion that the best combination has always been chosen in response to changes in the market of energy sources in Japan and that the current combination of electro dialysis, multiple-effect evaporator and co-generation is the best of all industrial processes for manufacturing salt from seawater. As for optimum take-over brine concentration from electro dialysis to evaporation, it is concluded the higher the better. The present electro dialyzer is operated in conditions which produce a brine of about NaCl 200 g/l to avoid CaSO₄ scale problems. However, about 50 kWh of exergy consumption will be reduced in future for production of a ton of salt by using high performance membrane capable of producing a brine of NaCl 300 g/l.

INTRODUCTION

In Japan, where no rock salt is produced and climatically the annual amount of rainfall is almost equal to that of evaporation, salt has been traditionally produced by thermal evaporation of brine concentrated by means of salt fields particularly developed in this country. Today the salt manufacturing process in Japan is composed of three sub-processes, production of brine by concentrating seawater, crystallization of salt by evaporating the brine, and utility which supplies energy in the required forms.

All the salt production processes discussed in this paper are combinations of the above sub-processes and the study was conducted first on each sub-process and then on their combinations, and their cost is analyzed in terms of energy.

RESULT AND DISCUSSION

The salt production cost can be broadly divided into energy cost, capital cost, and labor cost. In this paper, however, the economic comparison of various processes is solely based on unit energy cost, for the following reasons. The energy cost V required for the operation of electro dialyzer and evaporator accounts for virtually all of the variable cost for these equipment. It is a function of the production rate p as in the case of other equipment and can be expressed as:

$$V = e_0p + rp^2$$

In the above equation, the first term on the right side is the so-called theoretical energy cost, with e_0 representing a cost coefficient corresponding to the theoretical potential difference and the second term

is the cost of transfer energy, with r representing a cost coefficient corresponding to transfer resistance. Both e_0 and r are proper to the equipment used.

The costs other than the energy cost, namely, the capital cost and labor cost are fixed. With these fixed costs given collectively as F , the total cost TC and the unit total cost UTC are expressed as follows:

$$TC = F + V = F + e_0p + rp^2 \quad (1)$$

$$UTC = TC/p = F/p + e_0 + rp \quad (2)$$

The production rate that optimizes UTC becomes equation (3) from equation (2).

$$p(\text{opt}) = (F/r)^{0.5} \quad (3)$$

and the various unit costs at the optimum production rate are:

$$UVC(\text{opt}) = e_0 + (Fr)^{0.5}$$

$$UFC(\text{opt}) = (Fr)^{0.5} = UVC(\text{opt}) - e_0$$

$$UTC(\text{opt}) = e_0 + 2(Fr)^{0.5} = 2UVC(\text{opt}) - e_0$$

Since it is easy to divide UVC into the theoretical unit energy cost e_0 and the unit cost of transfer energy rp , the unit total cost at the optimum production rate can be readily obtained from the above equation.

Furthermore, assuming that the actual production rate is α times the optimum production rate, the unit total cost can be obtained as follows:

$$p = \alpha(F/r)^{0.5}$$

$$UVC = e_0 + \alpha(Fr)^{0.5}$$

$$UFC = 1/\alpha(Fr)^{0.5} = (UVC - e_0)/\alpha^2$$

$$\begin{aligned} UTC &= e_0 + [\alpha + (1/\alpha)](Fr)^{0.5} \\ &= e_0 + [1 + (1/\alpha^2)](UVC - e_0) \end{aligned}$$

It was not until the early 1950s that an industrial process began to be used in place of the traditional agriculture-like method in Japan. Subsequently, new processes emerged as shown in Table 1 and since 1972 all of the salt producers have been practising the currently employed combination of sub-processes — electro dialysis for brine production, multiple-effect evaporation for salt crystallization and co-generation by a boiler and turbine for utilities. Before 1972, the processes shown in the table had been in use only partially, with most salt pro-

TABLE 1

Industrial salt manufacturing processes employed in Japan

	Brine producing sub-process	Salt crystallization sub-process	Utilities sub-process
1950s	Vapor compression (VC)	Vapor compression (VC)	Purchased power
1960s	Electrodialysis (ED)	Vapor compression (VC)	Purchased power
1972-	Electrodialysis (ED)	Multiple-effect evaporation (MEE)	Co-generation

ducers employing a combination of salt field and multiple-effect evaporator.

The earliest substitution for the salt field method as a brine producing process was vapor compression. However, this process was supplanted, without wide acceptance, by electro dialysis upon commercialization of the latter, because of its lower energy consumption as shown in Fig. 1, in which the horizontal axis shows water ratio, the quantity (t) of water in the brine which contains 1 t of salt, as an expression of brine concentration. The electro dialysis curve and the vapor compression curve show energy requirements to concentrate seawater to a given level of water ratio by electro dialysis and vapor compression respectively.

Vapor compression was employed as a salt crystallization process, as well, in place of multiple-effect evaporation. Eventually, however, the latter process has revived, since it consumes the least energy when combined with co-generation.

Only heat, unlike other forms of energy, is partially useful as effective energy, with the remainder being discarded. The theoretically maximum amount of effective energy is called exergy, and exergy (E) in an open system is expressed as:

$$E = e G = [(h-h_0) - T_0(s-s_0)] G$$

where e = specific exergy; h = specific enthalpy; s = specific entropy; T = absolute temperature, subscript 0 refers to base condition which is determined by site conditions. Specific exergy is a state variable; therefore, energy balance can be obtained by using exergy.

Table 2 shows the results of heat evaluation in term of exergy which was conducted for economic comparison with other forms of energy. As is evident from these data, multiple-effect evaporation, when combined with co-generation, is the most economical salt crystallization process.

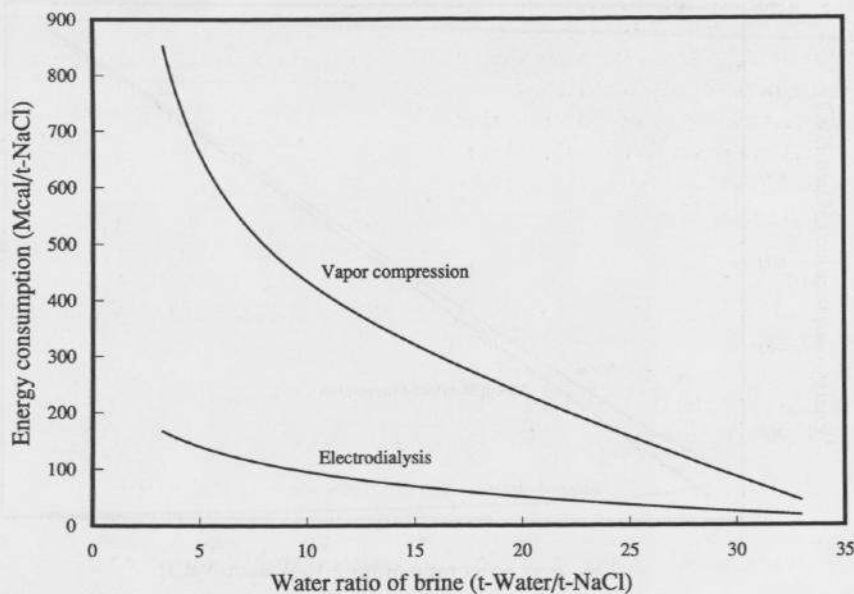


Fig. 1. Comparison of energy consumptions between brine producing processes.

It is thus clear that the currently practised combination of sub-processes is the most advantageous in respect of energy consumption.

To further enhance the economics of the salt producing operation, it is necessary to determine the optimum take-over brine concentration, i.e. the optimum concentration of brine for transfer from brine producing process to salt crystallization process. In Fig. 2, the horizontal axis shows water ratio. The electro dialysis curve shows the theoretical energy requirement to concentrate seawater to a given level of water ratio by electro dialysis, as obtained from

$$E = k \ln(W_0/W)$$

where W = water ratio; subscript 0 refers to diluting cell of electro dialyzer and k is the experimentally obtained constant 22.2 (kWh/ton NaCl). The multiple-effect evaporation curve shows the energy requirement to achieve salt crystallization from a given level of water ratio by multiple-effect evaporation, as obtained from exergy balance.

Another element that must be considered in determining actual energy requirement is an ohmic drop caused by electrical resistance of the electro dialysis cell. However, if this element is optimized within a given amount of capital investment in equipment, it may be neglected in the determination of the optimum take-over brine concentration.

Figure 2 shows that optimum take-over water ratio which minimizes total energy consumption is very low. Thus, as for take-over concentration of

TABLE 2

Summary of case study on the exergy consumptions (Mcal/t NaCl) for crystallization processes

Type of exergy and (efficiency of conversion)	Type of crystallization process		
	Vapor compression	Multiple-effect evaporation	
Theoretical (Adiabatic)	150 (0.83)	155	-
Kinetic power (Machine, motor)(0.95)	180	-	-
Electric power (Turbine generator) (0.86)	190	-	-
		H.P. Boiler co-generation	L.P. Boiler
Steam (Boiler)	220 (0.38)	155 (0.38)	155 (0.22)
Fuel	575	410	710

brine from electro dialysis to crystallization, the higher the better in so far as the brine is not saturated with NaCl.

At present, electro dialyzers are operated in conditions which produce a brine of about NaCl 200 g/l to avoid CaSO_4 scale problems. However, if we can use high performance membrane which produces a brine of NaCl 300 g/l, about 43 Mcal/t or 50 kWh/t of exergy consumption will be reduced.

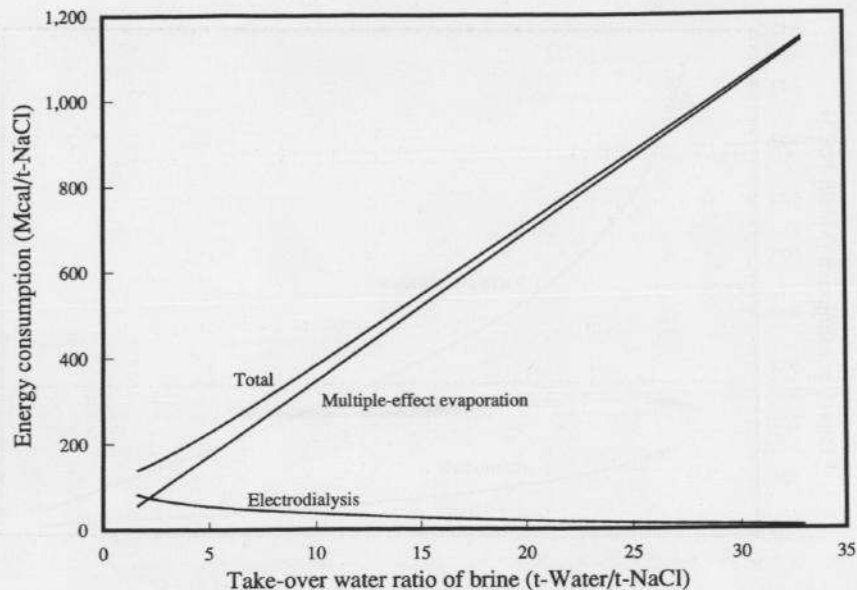


Fig. 2. Energy consumption vs. take-over water ratio of brine.

CONCLUSIONS

The study led to the conclusion that the best combination has always been chosen in response to changes in the market of energy sources in Japan and that the current combination of electrodesialysis, multiple-effect evaporator and co-generation is the best of all industrial processes for manufacturing salt from seawater.

If we can use high performance membrane which produces a brine of NaCl 300 g/l, about 43 Mcal/t or 50 kWh/t of exergy consumption will be reduced.

REFERENCES

Rant, Z. 1956. Forschung (in German). 22 (1): 36-37.