STEAM PLANT ASPECTS OF SEAWATER DISTILLATION

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Contents

Summary

This is a review which summarizes activities, relevant to the steam plant interests of Mechanical Engineers, in a field with which I have been associated for some twenty years. Its drafting began as a possible submission to the 1977 Conference of the Steam Plant Group of the Institution, but it turned out to be rather too long for inclusion in that Conference. Nevertheless there are many who felt that it was a record and summary of some interest and that its publication as a monograph would be worthwhile.

In making this survey I cannot pretend to have been able to get far enough away of gaze with an impartial view. The range is vast, selection is necessary, and choice has inevitably an element of personal assessment. So also has narrative and comment. There are no doubt aspects of importance which I have unwittingly omitted, as well as others on which some may feel my comments to be inadequate, or unjustified, or both. But I have tried to give a reasonable reflection of the situation as I see it, "warts and all", and recognize that some of the warts may be my own.

1. Introduction

In 1964 I had the privilege of giving a Nominated Lecture to the Institution of Mechanical Engineers on "Fresh Water from the Sea" (Silver 1964). At that date the first commercially viable desalination unit of 1 million imperial gallons per day (mgpd) (4530 m^3 day^{-1}) had been in service for only 4 years. It operated on the then novel multi-stage flash (MSF) distillation process. The contemporary scene then was of fairly strong, almost partisan, advocacy of several different processes, classifiable in three groups, viz. (a) distillation processes other than MSF, (b) processes based on freezing seawater and separating out the ice crystals before remelting, and (c) membrane processes, including reverse osmosis. There was also at that time some uncertainty as to the extent to which a desalination market would actually develop, despite several forecasts of the growing need for supplementation of water resources.

Fourteen years later it is now evident that a major market exists and that desalination has had a major influence on economic and social development. This fact will be described and discussed in some detail later because its implications are very important. Meanwhile, however, we note particularly the technological aspect that the MSF process initially ousted all alternative distillation processes, and has since been the predominant technique in all commercial desalination up to now. It is interesting to note that the basic MSF patent (Silver 1957) was filed in 1957, so that this review follows 20 years' experience.

The life of a plant is important for the assessment of cost of its product, and initially it was uncertain as to what lifetime could properly be assumed for MSF plant. We now know (1977) that the first MSF units (two of 1 mgpd each constitute the E plants at Kuwait) have functioned for 17 years, with normal maintenance. No satisfactory commercial development of either freezing or membrane processes for desalination of seawater has occurred. Interest in the possibilities of freezing processes has waned and can now be said to be moribund.

There are good technical reasons for believing that it was never likely to succeed (Silver 1974) and interest is unlikely to be revived. With membrane processes however the situation is very different. There are good technical reasons for believing the reverse osmosis is likely to be suitable engineering method for desalination (Silver 1974) - provided a chemically and mechanically satisfactory membrane system can be found. Interest in possible developments of this type of process is certain to continue.

But an interesting technological feature of today is the revival of interest in distillation methods other than MSF. The situation is that the tremendous expansion of the desalination market made possible by MSF, and the accumulation of practical experience which this has engendered, has promoted a far better understanding of the problems arising in any desalination context.

At its most elementary level this can be stated as a firm, if belated, realization that no practically available separating force can match the Archimedes forces which separate vapor from liquid under gravity. It is this elementary fact which gives distillation a head start over any possible competitor. At the more sophisticated level it is that the massive experience now accumulated with MSF operation can contribute to any and all distillation processes. In the light of that experience and, of course, of our increased knowledge of the weaknesses as well as the strengths of MSF, it may be timely to re-examine alternative distillation methods. Some such proposals are discussed later.

The impetus for all such activity is that desalination is essential in the modern world. It is therefore worthwhile including an outline of the fundamental reasons for this situation, and we give this in the next section.

2. The Need for Desalination

Desalination is essential because water is essential. That statement would have been nonsense before the industrial revolution, and so long as industrial production occurred only in portions of the world with plenty of natural water to spare it was still nonsensical or irrelevant. But in the modern world, when every country seeks to advance by industrial growth, it becomes vitally true. In the industrial activities of the modern world, one ton of an industrial product represents an average use of the order of 200 tons of water (Silver 1976). Without water in large quantities industrial expansion or development is impossible. Economic historians who ascribed the 18th century industrial advance of Europe to the energy of coal took the water for granted. But the advance was only possible because we had *both* fuel and water - the fuel for power and the water for process. No textile development, no metallurgical development, no chemical development, no social development, would have been possible, without water. Correspondingly, present-day western economists and politicians, who have only belatedly come to realise the crucial dependence of economic growth on energy, have not yet awakened to the fact that it is just as crucially dependent on water. This has however been clearly realised in the new nations of the Middle East such as Kuwait and Saudi Arabia. The essential feature in their development consists in using a proportion of their fuel resources to produce fresh water by desalination. This is the essential basis not only for domestic supply but for industrialization.

In my nominated lecture in 1964 I gave some preliminary data on the relative consumptions of energy and water in modern civilization. These figures were studied further and the United Nations Resources Division adopted a figure of 5 gals kWh^{-1} for planning purposes for developing countries. This is the minimum ratio of water consumption to electricity consumption which is recommended as compatible with modern industrialised standards of living. A lower value is unsatisfactory, restricting economic and social growth. It is of interest to note that in 1972 the value for the UK was 6.7 gal kWh^{-1} compared with 10 gal kWh^{-1} in 1960 (Silver 1976). How much lower can it be allowed to fall without restricting the economic growth on which the UK is said to depend? It seems unlikely that the position of a major industrial nation could be maintained on the minimum proportion recommended for developing countries.

Of course in the UK the possibility exists of increasing the proportion of precipitated water which is actually used, and the water authorities are certainly alive to this possibility. The immediate future is likely to see important proposals for new ways of water management, of reservoir construction, of river control, of treatment to enable water to be used several times. But all such changes from traditional water management not only introduce additional direct costs but impinge on agricultural, transport and amenity interests, and so incur indirect costs which, while difficult to assess precisely, are undoubtedly severe. Hence it is possible in principle that water costs in non-arid countries will rise to a level where desalination will be a preferable alternative.

Thus we may say that while desalination has so far impinged on the mind of the general public mainly as a contribution to the domestic water supplies for hygiene in arid countries, its real scope in such lands is to provide the essential basis for industrial development. Furthermore it may also be required as a supplement to maintain industrial momentum in non-arid areas. These are the two vital factors which ensure a large and expanding market for desalination.

Perhaps a concluding remark may be made in this section regarding the emphasis we have put on industrial activity while agriculture has only been mentioned incidentally. Again a romantic popular notion of desalination is that deserts may be made to flourish by its help. The extent to which this can occur is difficult to assess not only because of direct cost factors but also it raises questions of overall political planning. The quantity of water per ton of industrial product has already been stated as averaging 200 tons. But for a ton of average agricultural product the figure required even in highly skilled irrigation is of the order of 1000 tons and upwards. Hence a fuel-rich arid country has particular problems in establishing a policy of industrialization relative to agricultural growth. The rate of desalination planned has to be divided between industry and agriculture in the foreknowledge that every 5 tons of industrial product sacrifice a possible ton of non-imported food. Even a country such as the UK with agriculture based traditionally on direct precipitation may have to include such considerations in future planning, in so far as increased catchment schemes may reduce river and small stream flow, thus affecting agriculture.

All this discussion is background, but it has been desirable to give it in order to throw into relief the outstanding significance of desalination in the modern world. The direct interest of the mechanical engineer arises from the situation that, given the necessity of desalination, and given that any desalination process requires a consumption of energy, the vital problem of engineering design is to devise a process which will be as economic as possible in energy consumption and in capital cost. So we can now return to the actual technologies, for all contemporary discussion or advocacy of alternative processes is based, ultimately, on energy and capital economy comparisons.

3. Energy Requirements of Desalination

While these have been discussed in detail in many papers, it will be helpful in presenting a continuous narrative in this present review to summarize the situation.

The thermodynamic free energy difference between pure water and seawater is 2.8 kJ kg^{-1} of pure water. The average present day thermal energy requirement in the distillation process is 260 kJ kg^{-1}. The gulf between these values is caused by a combination of the second law of thermodynamics, other physical phenomena and financial constraints. The way this combination operates can be seen from the following brief analysis.

The free energy difference is reflected in the boiling point elevation. Taking this as of the order of 0.5 K, and if the distillation process operates over a temperature range of 373-310 K, the second law alone establishes an energy requirement of 0.5/63 h_{fg}. The mean value of h_{fg} in the temperature range is 2340 kJ kg^{-1}, giving 18.6 kJ kg^{-1}. However the need to have finite rates of flow of vapor, which arises from keeping down the size of plant, implies pressure drop associated with temperature differences additional to the boiling point elevation, and from this cause alone we may have 2 K of difference, giving 2.5 instead of 0.5, and so raising the requirements to about 90 kJ kg^{-1}. Finally to keep the capital cost down we also require not only finite rates of flow but finite temperature differences for heat transfer and such considerations readily add effectively another 5 K of difference, giving 7.5 and so indicating a requirement of the order 270 kJ kg^{-1}.

The values are, of course, improved by using a larger temperature range. If the top can be extended to 395 K and the bottom to 300 K the requirements are reduced in the ratio 63/95 giving respectively 12.3, 60 and 180. All the ingenuity, all the research and development, all the possibilities of reducing the energy needed for desalination by distillation, are concerned with (a) reducing the operating temperature difference total or (b) extending the temperature range, without incurring excessive capital cost or disturbing reliability and ease of operation.

It is against that background that the present achieved level of the order of 260 kJ kg^{-1} has to be seen - and it is for these fundamental reasons that I have felt reasonably confident in predicting that we are unlikely ever to devise a satisfactory distillation process with thermal energy requirement less than 150 kJ kg^{-1} (Silver 1974).

These figures refer to thermal energy supply to the heat input section of the distillation plant. In assessing the actual economics of desalination it is necessary to refer them back to prime fuel consumption. When a plant is designed for water production only, the thermal supply is directly the prime energy consumption. But when, as is most frequent in practice, the thermal supply is by bled steam from a power production turbine (dual-purpose plant), the prime energy consumption is much less. The actual value can only be calculated for a specific turbine cycle.

In discussing this point I shall adopt a procedure which may need a word of explanatory apology to those engineers who are well aware of the precision with which the thermodynamic performance of complex steam turbine circuits can be evaluated, including reheating, regenerative feed heating, provision of services and the like. It is perfectly possible to give precise analytical formulae for specific cases. For my purpose at present however I want to establish certain fundamental principles the significance of which can be hidden or lost in such detail, while the trend and order of magnitude of their effects is all important. Accordingly I shall use a very simplistic analysis which may shock the purist, but which nevertheless gives the correct conclusions.

This basic principle is that when a thermal service is provided by withdrawing turbine steam from a stage above the condenser, the conversion efficiency for unit mass of steam thus withdrawn is reduced. For a service at the temperatures required for desalination the reduction may be taken as of order ¾. Thus, per unit of power produced we have to supply at the boiler 4 instead of 3 units thermally, and 3 units are now rejected thermally to the service instead of only 2 units to the condenser. Since the rejection to the condenser was totally unused, the upshot is that we have maintained the same power, and attained the thermal service of 3 units, at the cost of only one unit additional consumption. From the point of view of power generation alone, the result would be disastrous. The "efficiency" has gone down from, say 38 to 28.5 per cent, the quantity of steam flow is increased by 33 per cent, and hence the size of boiler, piping, stages, etc., all require substantial increase. But all these can be accepted if the service obtained is sufficiently valuable. It is also important to note that the order of magnitude calculations we are using can be taken as linear - i.e. the factors can be applied to any fraction of turbine steam modification. Thus if the desired service can be obtained by withdrawing only 10 per cent of the main steam flow, the prime energy cost of 3 service units is still unmodified at 1 unit, and the "efficiency" of power production, if 38 per cent unmodified, is reduced to 0.9×38 + 0.1×28.5 = 34.5 per cent.

Now comes a point which is of very great importance in the practical application of distillation, as will be seen later. At the beginning of this section it was shown that the basic thermal input is proportional to effective temperature difference divided by the operating temperature range. Apparently therefore there would be a very substantial advantage to be gained by increasing the temperature range. However it happens that the replacement factor - given as of order 0.33 in the preceding discussion - is also approximately proportional to the temperature range. It follows that there is in fact no first order benefit in prime energy consumption by increasing the temperature range when distillation plant is coupled with power production. Failure to appreciate this point fully has had some effect on research and development effort which is discussed in section 5 when dealing with the problems of temperature range.

These augments adequately cover the thermal input requirements of the thermal service. However we have additionally to recall that a desalination service will have a requirement also for power to pump the feed, product, and any recirculation, in the circuit. The power may be only a small proportion of the required thermal energy input - in present day MSF practice it is of order 5 per cent - but its effect on prime energy requirement is more substantial. On 100 per cent modification, using the preceding figures, 3 units of thermal service would require 0.15 units of power. To maintain the same saleable power, the power production would have to go up to 1.15 and the prime energy consumption to 4.15, so that the "saleable efficiency" is reduced by the total modification in the ratio 3/4.15 instead of 3/4. In the example chosen this is from 38 to 27.5 per cent. On the 10 per cent service basis it is from 38 to 34.48 per cent.

The situation can be summed up by saying that the total energy replacement factor for a unit of thermal service is 1.15/3 = 0.383 - including the associated pumping power. In previous more general articles (Silver 1974, 1976) I have rounded this to 0.4. Excluding the auxiliary power requirement the appropriate figure is 0.33. The auxiliary power requirement varies between one distillation plant design and another, but the whole range can be encompassed in the statement that the prime energy required to provide a distillation service is not less than 0.33 and less than 0.4 of the thermal service requirement.

It is here that the operating temperature range does have an effect on prime energy consumption, because the pumping power required depends on temperature range. The situation is discussed in section 5.

These figures have a second order error on the safe side because of course the desalination pumping power is entirely dissipated as heat within the circuit and so contributes something to thermal supply. But since the dissipation occurs throughout the temperature range instead of all at the top temperature its effective contribution to reduction of thermal supply is only about half of the dissipated amount. The correction is therefore only of the order of 2 per cent.

It is for these reasons that I regard an energy cost, at present, of around 260×0.4 = 100 kJ kg^{-1} as properly indicative of present-day distillation technology when combined with power production. Projecting to the future we may reach a corresponding 150×0.4 = 60 kJ kg^{-1}, but are unlikely to do better than that.

Although this work is concerned with distillation, it may be desirable to complete the picture by indicating the comparative energy situation regarding desalination by freezing and by reverse osmosis. Similar thermodynamic reasoning suggests that the probable limit of required power input for freezing is 35 kJ kg^{-1} and for reverse osmosis 15 kJ kg^{-1}. Assuming that this power is generated by turbines of 38 per cent efficiency, the effective prime energy requirements are respectively 90 kJ kg^{-1} and 40 kJ kg^{-1}. Compared with the corresponding probable limit of 60 kJ kg^{-1} for distillation there is clearly no advantage in pursuing freezing methods. Indeed distillation with its present effective attainment of 100 kJ kg^{-1} is within reach of the probable limit ever likely to be achieved by freezing. In contrast there is a big margin in favor of reverse osmosis and research to further this process could be well justified. Finally, against the background of the water demand situation set out in section 2, we may close this section by considering the relative rates of power and water production which are possible. Evidently desalination, even if it costs nothing, can be of no real interest in practice unless the quantities producible are commensurate with the needs.

However the figures given in this section show that 1 unit of power production can be associated with 3 units of thermal supply to a distillation service. Thus 1 kWh of power can be give 10 800 kJ thermal supply. With existing distillation performance at 260 kJ kg^{-1}, this can produce 40 kg fresh water, i.e. approximately 8.5 gallons. We arrive at the significant result that a total combination of power production with its thermal rejection as thermal service can give a product ratio of the order of 8.5 gal kWh^{-1} i.e. commensurate with the known needed relative consumption in industrial countries (see section 2). This is the crucial result, which establishes that desalination by distillation is worth considering in the modern world. A power consuming process such as reverse osmosis has to be looked at in the reverse manner - given a social need for 5 gal kWh^{-1}, how will its power need compare with the magnitude of existing consumption? At 15 kJ kg^{-1} power requirement the power need for 5 gal is 340 kJ, i.e. approximately 0.095 kWh. Thus the increase in power facilities predicted for a total reverse osmosis water supply is of order 10 per cent, which again can be regarded as reasonably commensurate.

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