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On the significance of recirculation between intakes and outfalls of desalination and thermal power plants

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ABSTRACT

In this study, a quantitative analysis is performed to examine the effect of recirculation between intakes and outfalls to the operational performance of coastal desalination as well as thermal power plants. The results show that the effect to desalination plants is substantially more significant than that of thermal power plants, with the increase in salinity of the ambient waters near the intake having a direct impact on the operating cost of the desalting process. Thus, it is important to minimise the magnitude of recirculation for the desalination plant. The potentially higher initial capital cost required (such as placing the outfall further offshore) can be compensated by the corresponding savings in the operation cost in the long run.

Keywords: Recirculation; Intake; Thermal power plant; Desalination plant; Cost implications; Outfall

1. Introduction

The magnitude of recirculation of pollutant (i.e., heat, salinity, suspended solids, etc.) between the intake and outfall of a coastal facility is an important consideration for the engineering design and environmental assessment. Significant recirculation can lead to a large percentage of the discharge substance re-entering the intake. This could increase the processing cost of the operation, and can even disrupt the process at worst. Both are extremely undesirable from the operator's view point.

Historically, the issue of recirculation has received substantial attention for the engineering design of coastal thermal power plants. Many arrangements were adopted to minimize the recirculation in tune with the geometry of the local shorelines. An example can be found in the design of the Diablo Canyon Nuclear Power Plant in California, USA, whereby the intake and outfall structures are separated using a natural headland protrusion [1]. In such cases, the magnitude of recirculation can be expressed as a percentage of the exhaust heat reentering the intake, based on the temperature increase near the intake area attributable to the cooling discharge. For example, LaBelle and Bradley [2] examined the temperature tolerance during the power plant entrainment of copepods for the Chalk Point Steam Electric Station in Maryland, USA. In that study, they also reported another study [3] that the recirculation between the intake and outfall of the Chalk Point Steam Electric Station was around 10%.

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Compared to thermal power plants, the effect of recirculation to desalination plants has not been investigated extensively so far. A possible reason is that the brine flow rate from desalination plants had been relatively small in the past. Correspondingly, field studies to monitor the salinity increase due to the desalting operation are thus rare. However, significant cost reduction for desalination had occurred in the last two decades with the improvement in membrane technology as well as the substantial energy recovery of the brine [4]. In parallel, the size of coastal desalination plants is also escalating to achieve an economy of scale in the water production. The trend will likely continue in the future. This has led to more concern on the impact of brine discharges to the coastal environment, as well as the potential and magnitude of recirculation between the intake and outfall. In the few reported cases in the literature whereby the recirculation of a desalination plant is assessed, the analysis is often perceived to be similar between the desalination and power plants due to the similarity in the turbulent mixing of the salinity and waste heat concerned [5].

The build-up of ambient salinity near the intake can be attributed to two effects that occur simultaneously, namely near-field and far-field. Near-field recirculation refers to the active mixing with a relatively short time scale, whereby the brine plume spreads and propagates in the ambient coastal waters due to the initial momentum and buoyancy fluxes in such a manner that leads to a direct and immediate re-entrainment of portion of the brine back to the intake. The propagation would also depend on the vertical distribution of the desalination effluents in the water column, with the distinction between membrane technologies (the brine is denser than the ambient and hence would sink towards the seabed) and thermal technologies (the brine can be lighter or denser depending on the temperature and salinity range).

In a coastal area where the brine plume is subjected to oscillatory tidal currents, the near-field recirculation is not a concern when the tidal current flows in a direction that advects the plume away from the intake. However, when the tidal current reverses, the potential of near field recirculation becomes substantially more significant, and the worst case scenario typically occurs during this time interval. Adverse near-field recirculation can normally be avoided by properly selecting the outfall geometry, so that sufficient near-field dilution can be achieved in the immediate vicinity of the outfall and meet the ambient standard within a prescribed mixing zone. A good description on the near-field processes can be found in CORMIX [6].

Far-field recirculation refers to the residual salinity increase in the ambient waters due to the long term accumulation of salinity by the operation of the brine outfall. Far-field recirculation depends on various local ambient characteristics, including the amount of tidal flushing in the area, the seabed bathymetry and the shoreline geometry. References [7] and [8] presented simplified analysis to illustrate that the distance between the outfall and intake is the key factor controlling the amount of far-field recirculation if the water depth is relatively uniform. With a complex bathymetry, however, the situation is more complicated and residual salinity can be accumulated in pockets of low lying seabed undulations. Far-field simulations using comprehensive numerical models are then essential to deal with the complexity [9].

At any given time, a desalination plant would experience both near-field and far-field recirculation effects in a composite manner as demonstrated in the recent study [10]. As pointed out above, the effect of recirculation between the intake and outfall to coastal thermal power plants has been well addressed in the past. Comparatively, the effect of recirculation to desalination plants has not been discussed as much, and it is also often implied in the literature that the recirculation consideration is similar between the two. The objective of the present study is to distinguish the significance of recirculation to coastal desalination and thermal power plants using quantitative analysis. For comparison purpose, we shall review the recirculation consideration of power plants first in the following section, before addressing the considerations for desalination plants.

2. Thermal power plant

A simplified schematic diagram of a once-through cooling water system for a thermal power plant is given in Fig. 1. We assume that the cooling water system is designed to remove *X* watt of waste thermal

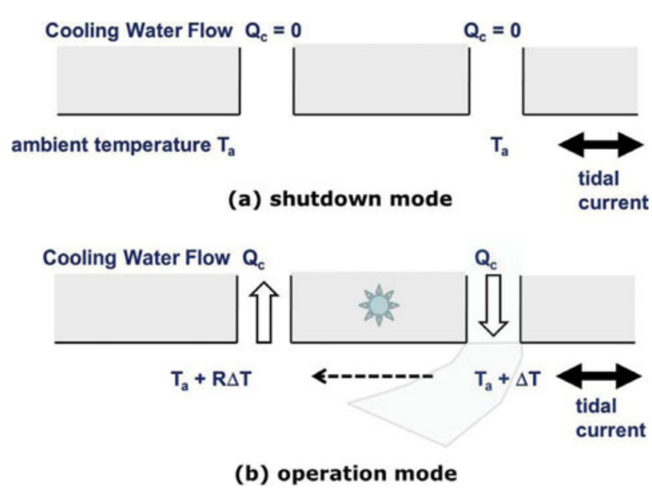

Fig. 1. Recirculation of a thermal power plant.

energy from the power system, and that there is no water loss in the process (i.e., make-up water is ignored). We define the value R to be the recirculation ratio of between the intake and outfall with $0 < R < 1$. For example, if the cooling water effluent has a temperature increase of 10°C above ambient, and it leads to an increase in the ambient temperature around the intake by 1°C, then $R = 0.1$.

The conservation of thermal energy in the system dictates:

$$C_p \rho Q_c (T_a + R\Delta T) + X = C_p \rho Q_c (T_a + \Delta T) \qquad (1)$$

where C_p is the specific heat capacity [J (kg°C)$^{-1}$], ρ is the water density [kg m^{-3}], Q_c is the cooling water flow rate [m^3 s^{-1}], T_a is the ambient temperature [°C] and ΔT is the temperature rise [°C] in the effluent. Note again that this is a much simplified analysis. In reality, the increase in ambient temperature at the intake may affect the heat transfer processes of the power plant in a non-linear manner.

From Eq. (1), this implies that:

$$\Delta T_0 = \frac{X}{C_p \rho Q_c} \qquad (2)$$

It is highly desirable to minimise ΔT. This would occur if recirculation does not exist, that is, $R = 0$, which is often the design condition. Without recirculation, the design temperature increase would thus be $\Delta T_0 = \frac{X}{[\![(C]\!]_p \rho Q_c)}$. With recirculation, Fig. 2 shows a plot of the non-dimensional temperature increase, $\frac{\Delta T}{\Delta T_0}$ against the magnitude of the recirculation ratio R. From the figure, it can be seen that the effect between the two is linear if the recirculation ratio is small, as follow:

$$\frac{\Delta T}{\Delta T_0} = 1 + R \quad \text{if} \quad R < 0.1 \qquad (3)$$

However, a further increase in R beyond 0.1 leads to an exponential increase in the discharge temperature which is thus undesirable.

In practice, from the author's experience, a worst case value of R higher 0.1 can mostly be avoided if proper considerations are taken into account towards recirculation in the design of the integrated intake and outfall system for a coastal thermal power plant. Another point to note is that if the recirculation can be kept small, the effect of the increase in ambient temperature to the power plant operation is then also small. This is because most power plants can cope with a range of ambient temperature fluctuations at the site. Finally, from Eq. (2), a complete short-circuiting would occur when $R = 1.0$ whereby ΔT approaches infinity. Obviously, this is only a theoretical scenario as severe disruption to the plant operation would have occurred beforehand.

3. Desalination plant

Fig. 3 shows a schematic diagram of the recirculation for a desalination plant. As seen in the figure, the flow system for the desalination plant is different from that of the power plant.

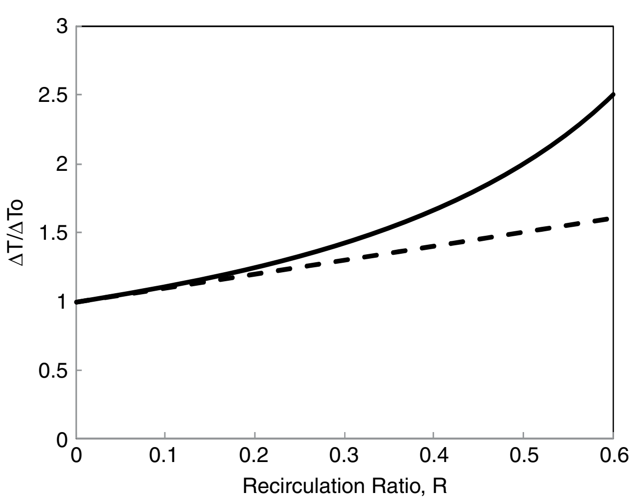

Fig. 2. Relationship between the non-dimensional temperature increase and recirculation ratio for a thermal power plant.

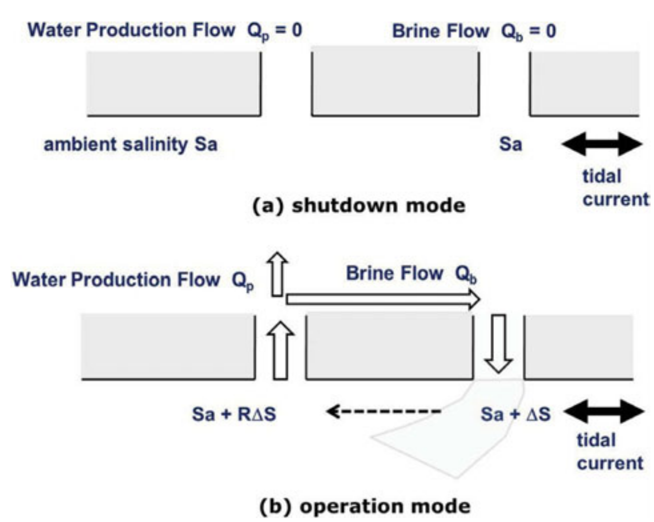

Fig. 3. Recirculation of a desalination plant.

The conservation of salt mass in the system dictates that:

$$(Q_p + Q_b)(S_a + R\Delta S) = Q_b(S_a + \Delta S) \quad (4)$$

where Q_p and Q_b are the freshwater production and brine flow rate [$m^3\ s^{-1}$] respectively, S_a the ambient salinity [ppt] before the operation of the brine outfall, and ΔS the salinity rise [ppt] in the brine discharges. This implies:

$$\Delta S = \frac{YS_a}{(1 - Y - R)} \quad (5)$$

Note that Y is the so-called recovery ratio which is equal to $\frac{Q_p}{Q_t}$ where Q_t is the total flow rate = $Q_p + Q_b$, and is currently ranging from 30% to 50% for most RO desalination plants. Obviously, it is desirable to minimize R for the reason that ΔS and hence the desalting cost will be reduced. Without recirculation, that is, $R = 0$:

$$\frac{\Delta S_0}{S_a} = \frac{Y}{1 - Y} \quad (6)$$

where ΔS_o is the salinity rise assuming that the ambient water characteristics remain unchanged, which is often the design value. Fig. 4 again plots the non-dimensional salinity rise, $\frac{\Delta S}{\Delta S_0}$, versus the recirculation ratio, with the recovery between 30% and 50%.

Again, it can be observed that the salinity rise increases with the recirculation coefficient similar to the power plant, and that the dependency is linear when the recirculation ratio is less than 0.1, that is:

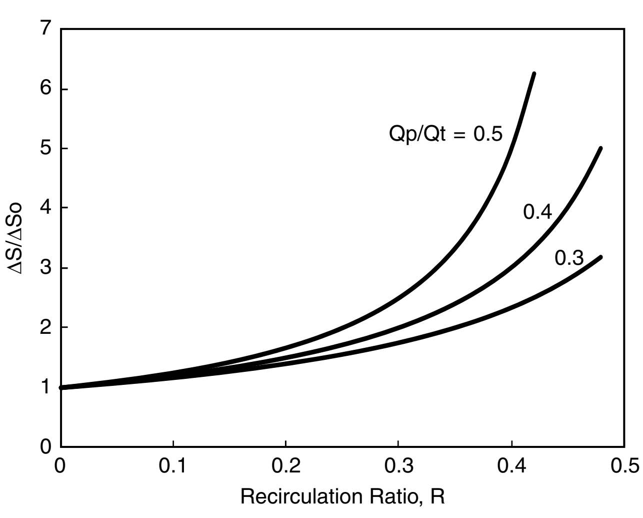

Fig. 4. Relationship between the non-dimensional salinity rise and recirculation ratio for a desalination plant.

$$\frac{\Delta S}{\Delta S_0} = 1 + \frac{R}{1 - Y} \quad if \quad R < 0.1 \quad (7)$$

However, comparing to Eq. (3), the rate of increase has an amplification factor of $\frac{1}{1 - Y}$. Since Y is in the range of 0.3–0.5 at present for RO desalination plants, the amplification factor is thus approximately 1.4 to 2.0. In other words, the rate of increase is much more significant in the case of a desalination plant. From Eq. (5), a complete short-circuiting would occur when $R = 1–Y$. Assuming a recovery ratio of $Y = 0.5$, the short-circuiting R is therefore only 0.5 which is significantly below the critical value of 1.0 for power plant. The analysis thus illustrates that recirculation is a much more significant consideration for a desalination plant. Finally, it should be noted here that the principle of the analysis for a thermal desalination plant (with brine that has both elevated temperature and salinity) can be viewed as a synthesis of the above analysis for both temperature and salinity, although the recovery ratio for thermal desalination plants is typically lower than that of the RO desalination plants.

Let's also examine how the recirculation of a desalination plant implies in terms of operating cost. Unlike a coastal power plant which can typically cope with a range of temperature fluctuations at the intake without a significant change in efficiency, the operating cost of a desalination plant will escalate with the ambient salinity since the plant needs to spend more energy to remove the additional salinity induced by the recirculation. Assuming that the operating cost will at least increase linearly with the salinity at the intake, the percentage of cost increase will then be:

$$\%\ \text{cost increase} = \frac{R\Delta S}{S_a} \times 100\% = \frac{RY}{1 - Y - R} \times 100\% \quad (8)$$

Fig. 5 shows a graph of the % cost increase due to recirculation for recovery rates between 30% and 50%. The dependency is clearly nonlinear. With a small ratio of $R < 0.1$, it can be computed that:

$$\%\ \text{cost increase} = R^2 Y(1 - Y) \times 100\% \quad (9)$$

However, when R increases further, the % cost increase becomes substantially higher to the power of R^2. This is highly undesirable to the desalination plant operators because the contract cost for the water production may be fixed [11] and thus the additional cost will have to be borne by the operator with a reduced profit margin or even resulting in operating loss.

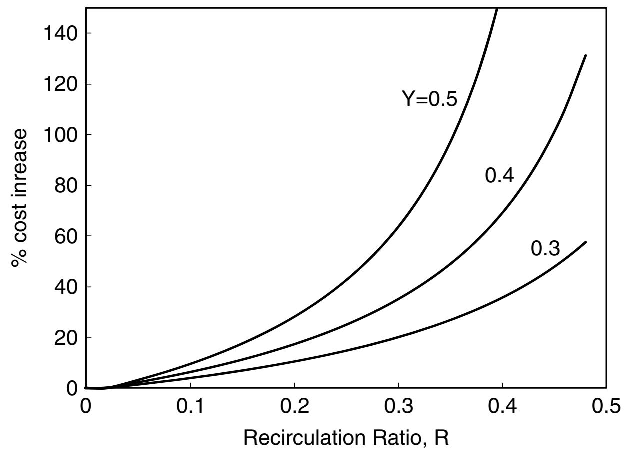

Fig. 5. Relationship between the % cost increase and recirculation ratio for a desalination plant.

Finally, it should be remarked that another concern for the recirculation of a desalination plant is the persistency of high salinity in the coastal waters. Whereas thermal cooling discharges can rely on the air-sea interface exchange to dissipate the heat in the ambient water, the salinity discharged by the desalination plant does not have an equivalent process. This is another factor that should be considered when balancing the capital cost for the intake and outfall structures towards the reduction of recirculation.

4. Conclusions

In this study, a quantitative analysis is performed to show that the effect of recirculation is substantially more significant to desalination plants than coastal thermal power plants. The increase in salinity of the ambient waters around the intake by recirculation will have a direct impact on the desalting cost. Thus, it is important to reduce the recirculation between the intake and discharge outfall of desalination plants. Various engineering measures can be taken towards the reduction, for example, the use of multiport diffusers as described in [12] or by lengthening the outfall pipe offshore as shown in [8]. The higher initial capital cost required (such as placing the outfall further offshore) can be compensated by the corresponding savings in the operation cost in the longer run.

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