CHAPTER VI
FINDINGS AND CONCLUSION

The present work on the design, construction and performance and heat extraction studies of a full scale 500m$^2$ salinity gradient solar pond developed at Pondicherry (India) comprises of experimental investigations on the actual pond and theoretical investigations through mathematical modeling. The mathematical model chosen is a one dimensional three zone model employing energy and mass balances. The governing equations have been solved using weighted average Unite difference method. This model is capable of incorporating a wide variety of initial and boundary conditions. The modeling studies not only predict the performance of the pond but also helps in fixing the thicknesses of the NCZ, LCZ and UCZ.

The important findings of the studies conducted are given in the following pages.

6.1 DESIGN, CONSTRUCTION, OPERATION AND MAINTENANCE

The Pondicherry Solar Pond is intended to deliver a heat energy output of 500KWh. The design values arrived at for the pond parameters are:

1. The zone thicknesses, evaluated using the modeling studies for obtaining optimum temperature of the HSZ, are: NCZ thickness 1.3m, LCZ thickness, 0.9m and UCZ thickness 0.25m giving a total pond depth of 2.45m.
2. The wall slope of 1:1 arrived at using Akbarzedah and Golding criterian.
3. Based on the load, the parameters obtained are

a) NCZ-LCZ interface area: \(404 \text{m}^2\) (20.6 X 19.6 m)

b) Bottom floor area: \(343 \text{m}^2\) (19.3 X 18.3 m)

c) Top surface area: \(497 \text{m}^2\) (22.8 x 21.8 m)

d) Volume of the heat storage zone: \(346 \text{m}^3\)

So the pond has a trapezoidal shape.

With an expected efficiency of 13%, the finite element analysis leads to bottom floor area of \(353 \text{m}^2\) and LCZ thickness of 0.91m almost agreeing with \(\text{llc}\) results already obtained. The expected volume flow rate and temperature drop to obtain 500 KWh output in one hour peaking mode operation are 55.68 m-Vhour and XT respectively.

The Pondicherry pond site satisfies almost all the essential and desirable requirements of a good pond site such as use for the energy extracted, access to salt, access to water, high insolation (for more than 300 days a year), high water tabic depth (>15m), and low wind speed (due to the natural topography and ceo friendly wind barriers), except that the soil has high permeability ranging from \(1.72 \times 10^{-6} \text{cm/s}\) to \(8.3 \times 10^{-3} \text{cm/s}\) measured using a precision permeameter. So compaction of the pond floor and bund and use of compacted clay and Low Density Poly Ethylene (LDPE) film for the containment of the pond brine without leakage become necessary for the pond.

The first lining scheme with two LDPE liners, bentonite and China clay powder mixture layers and sand as cushioning material leaked due to fractures in the LDPE liner.
The seams must be oriented down the slope walls (not across the walls) as otherwise hydrostatic pressure will weaken the film joints leading to fracturing and puncturing of the film.

The tensile strength studies indicate that the LDPE film in direct contact with brine solution at a constant high temperature looses its original characteristics and becomes susceptible to fractures.

The LDPE film degrades very easily when exposed to solar radiation directly. The FTIR studies indicate that such a LDPE film undergoes photo-degradation in which long alkyl chain polymers are homolytically split into smaller units leading ultimately to unsaturate and radical site formation. These chemical changes lead to reduction in the tensile strength of the films exposed to sun light, making the films to be prone to fractures and cracks. The LDPE film should be used only as submerged membrane when high temperatures are involved.

When the blades with 90º bend of the indigeneously developed film sealing iron are replaced by smoothened edges with 45º bend the weakening of the edges of the thermally welded joints have been enormously reduced and heat sealed joints having a tensile strength somewhat close to that of a single weld-free LDPE film could be obtained.

The optimum heat scaling width could be 7.2 cm with full overlap of the film or a 6.0cm wide single heating triple sealed joints.
Local clays at Kundikuppam and Pakkiripalayam villages which are of CL type and that at Thondamanatham village which is of CM type, have low-permeabilities and are quite suitable for pond lining applications. The CL type appears to be better because of its comparatively low shrinkage limit and less swelling when in contact with water and is preferred for the pond lining. This local clay costs 1/10th of the cost of bentonite clay and can be procured without any waiting time and hence has the added advantage. Cement grouting along the anchor trench and inserting country bricks in a matrix form along the slope walls and plastering the hund as well as the slope wall avoids erosion and slumping of the soil and consolidate the hund and slope walls.

The compound lining scheme with bentonite and China clay powder, compacted local clay between the LDPE films, river sand cushion and a sacrificial LDPE film for avoiding the mixing of brine with compacted clay and for solar energy collection also developed leakage with brine at temperatures of 80°C and above.

Fractures in the sacrificial layer and mm holes and punctures in the film next to the sacrificial film have been noticed. The LDPE liner must not be used even as sacrificial layer as its tensile strength characteristics get drastically altered at high temperatures making it susceptible to fractures.

The constant service temperature on the LDPE liners should never exceed 70 or 75°C.

Soft cushioning materials must be provided above and below the liner in order to avoid mm holes and punctures.
The degradation of LDPE film is temperature dependent, higher the temperature, faster the degradation and lower the mechanical strength. At higher temperatures the LDPE film has a very low puncture resistance even for fine grain sand loading.

Poorly conducting low cost rice husk ash has been found to be a good cushioning material for safe guarding the LDPE film against punctures.

The surface area of the LDPE film increases with temperature (about 7° to 187° for different films) resulting in the bulging of the film which in turn produces a little convexity of the membrane leading to uneven heating of the pond brine.

Though the chamber brick has three times the compression strength of country brick, as the thrust of the pond water column (of 2.45m) is expected to be only 0.275 Kg/cm², for cost effectiveness, country bricks have been used for the wails of the pond.

Black sand stone (called Cuddapah stone) is stable even at high constant service temperature of 110°C without layers peeling off or the stone becoming brittle or the stone developing cracks, could serve as sturdy impermeable top of the lining scheme.

Increasing the thickness of the compacted clay could also reduce the constant service temperature on the top most LDPE liner.
The improved composite lining scheme consisting of hentonite and China clay powder, compacted local clay, river sand, rise husk ash cushion, ihrec LDPE liners, concrete top over which the Cuddapah stones are laid and anti-corrosive cpnxv paint (Corrosolve IPN 800) coating of pond could contain the pond brine leak-free and the pond has trouble free leak proof operation over the past 1.5 years during all the seasons.

Forced circulation method of dissolving the salt which is simple and less time consuming and in which scum and other floating materials could be easily removed, is found quite suitable for salt mixing.

A 90cm dia semicircular acrylic vertically movable injection diffuser with a gap width of 3mm which gives a brine exit velocity of 1.203 m/s obtained for an injection Froude number 18 taken to ensure that mixing occurs more or less at the diffuser level is found to be adequate to establish the pond using Zangrarulo’s redistribution method. The semi-circular diffuser with closed flat portion facing the wall avoids local mixing due to the reflected brine from the wall.

A simple, low cost innovative in-pond passive salt dozer developed using bore well casing UPVC pipe and ribbed pipe with end-capping arrangement installed with simple masonry structure support, with the ribbed portion inside the HSZ has been found extremely suitable for replenishing the salt loss in the HSZ due to upward diffusion of salt from the HSZ, without affecting the NCZ and UCZ layers. This salt dozer uses the principle of gravity flow and convective mixing and does not require any power for its operation. Use of this in-pond dozer avoids mixing of the salt outside the pond and reinjecting it into LCZ which may some time result in differential heating of the pond floor and walls leading to the development of cracks in them.
During winter, the frequency of salt replenishment is low; however in summer, it has to be high. The rate of diffusion in summer is more or less constant. Addition of large amount of salt, does not alter the performance of the pond but helps in keeping salinity constant for a long time.

Adjusting of salinity at any level within the pond has been made possible using a vertically movable injection diffuser arrangement to inject either salt solution taken from the HSZ or fresh water taken from the top layered UCZ to the respective level, in order to add salt or dilute the solution of any layer without disturbing the layer above or below it.

The pond level has been found to decrease on an average of 2 to 5 mm/day. Evaporation loss and salt inventory studies indicate that there is no seepage of brine through the bed and walls of the pond. Making up of this level loss is done regularly by adding fresh water on top of the pond. Allowing the water to overflow for some time removes dirt and dust on the water surface thus improving the clarity of the top surface of the pond.

Surface flushing of UCZ layers to reduce surface water salinity caused due to migration of salt from HSZ to UCZ and salt replenishment at the HSZ are both necessary in order to keep the HSZ at the required salinity and heat extraction temperature of 70º to 75º C.

The application of sodium hypochlorite as algicide and aluminium sulphate as dirt settler have been effective in controlling the biological growth in the pond and improving the pond clarity.
The heat transfer surface area required to remove the heat from the brine flowing at the rate of 19 kg/s with a temperature fall of X °C so that 500KWh thermal energy could be extracted in a one hour peaking mode operation is found to be 55 m², i.e., 6 pipe lengths.

A low cost heat extraction system designed and fabricated consists of:

a) a Trombone cooler type counter flow heat exchanger with 6 pipe lengths.

b) a simple innovative brine extraction diffuser coupled to a brine circulation pump and

c) a portable reinjection diffuser which could be used for reinjecting the colder brine at any desired level of the LCZ.

Knowing the pump rate, the velocity of brine extraction and assuming a slit separation of 0.1m, the radius of the brine extraction diffuser works out to be 0.562m and a value of 0.6m has been used.

A simple low cost novel brine extraction diffuser with two semicircular parallel plate acrylic sheets of radius 0.6m and slit width 0.1m enables withdrawal of 55.68 m³ of hot brine without causing any turbulence and gradient /one erosion.

Innovatively coupling a foot valve to the top acrylic sheet of the brine extraction diffuser with a pipe welded to a coupling in the suction line provide Un manual priming operation and the need for very costly priming pumps has been eliminated.
6.2 TRANSMISSION RELATION

The radiation measurements made in the actual study pond has been utilized to fit a relation for the transmission function \( h(x) \) of an actual pond and the function is

\[
h(x) = 0.28 - 0.08 \ln(x)
\]

and is called the PP transmission relation which contrasts the Bryant and Colbeck transmissions relation (called BC transmission relation).

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h(x) = 0.36 - 0.08 \ln(x)
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The radiation at any level given by the PP transmission relation based on the actual pond measurements is in general smaller than that predicted by the BC transmission relation.

6.3 MODELING STUDIES

The simple model developed for the present studies indicates that the NCZ, UCZ and LCZ thicknesses affect the temperature buildup in the pond hut to different degrees. Due to the contrasting effects of decrease in heat loss from the HSZ and decrease of solar insolation reaching the HSZ depth with increasing NCZ thickness, the maximum temperature of HSZ increases, peaks up at a particular NCZ thickness and then decreases with the increase of NCZ thickness. A NCZ thickness of 1.3m at which the maximum temperature peaks up is taken as the optimum thickness for the
NCZ. The maximum temperature is not much different for the NCZ thicknesses close to this value (1.1m to 1.5m) and the pond could he operated for any one of these thicknesses. The minimum temperature does not show this effect but falls with decreasing NCZ thickness showing perhaps that the losses play a dominant role.

The variation of LCZ temperature with NCZ thickness/UCZ thickness/LCZ thickness shows more or less a sinusoidal swing over one year period. The minima occur at the 190th day after starting the pond i.e. in the last week of January and the minima show a large phase lag with the insolation minimum which normally occurs in November at Pondicherry.

The temperature build up in the pond is reduced with increase of UCZ thickness and 0.2 to 0.3m is the optimum UCZ thickness for a pond.

As the LCZ thickness increases, the maximum pond temperature falls; but the minimum temperature increases with increase, of LCZ thickness reaches a peak value and falls. Such a trend may be attributed to the effects of radiation absorption, thermal inertia and energy retrieval from the pond bottom. A LCZ thickness of 0.9m can be taken for the pond construction while the values ranging from 1.1 to 1.5m will also give nearly the same performance.

For the optimum thicknesses of NCZ, UCZ and LCZ, the pond could be used for extracting heat energy at temperatures of 70°C to 75°C for close to 90% of the days of a year.

The pond will begin to boil within one year period itself leading to adverse destablising effects unless heat is extracted from the pond.
Establishing a pond in July of a year after peak summer does not have any effect on its long term (one year) performance.

The water table depth has a pronounced effect on the temperature, the pond would attain a low small water table depth leading to low temperature attainment due to heavy losses while a high water table depth (>15m) leading to high temperature attainment due to low losses. The Pondicherry pond site has a water table depth > 15m satisfying this criteria. This study also shows that the heat extraction could be carried out for more than 90% of the days of a year at temperature above 70°C.

The ground thermal conductivity has only a very marginal effect on the temperature attainment as the water table depth is >15m.

The theoretical temperature profiles obtained using BC transmission relation and PP transmission relation show two maxima - one near the upper boundary and the other at the lower zone boundary in the initial period of heating and then the gradient formation takes place 30 days after the start of the pond heating process.

The BC transmission relation predicts higher temperature values for LCZ and NCZ layers than those given by the PP transmission relation and this is due to higher transmission fraction predicted by the relation at every level of the pond. The rate of heating falls as the temperature rises; but the rate of heating at any stage given by the BC transmission relation is higher than that predicted by the PP relation.
The BC transmission relation predicts 51 days whereas the PP transmission relation gives 67 days for the pond to reach 70°C to enable heat extraction process to be started.

Heat extraction could be continued up to 142nd day of starting the pond after which the pond has a cooling period and on the 190th day the temperature of the pond would reach the minimum value.

The BC relation predicts that the temperature falls by the same extent irrespective of the heat extraction percentage while the PP relation predicts a slightly steeper fall as the heat extraction percentage increases. The PP relation shows that on resuming the heat extraction, the pond temperature remained close to 75°C between 10 - 20% heat extraction while the BC relation predicts that at 10% heat extraction, the temperature of the HSZ would increase and reach 90°C while at 15% to 20%, heat extraction, the pond temperature would remain constant at 75°C. The BC relation predicts that the duration for which there is no heat extraction (when the temperature is <70°C) is constant for different percentage of heat extraction up to 20%, while the PP relation shows that this duration increases with the percentage of heat extraction. The differences in the prediction may be attributed to the higher percentage of insolation predicted by the BC transmission relation at every level of the pond.

### 6.4 PERFORMANCE ANALYSIS

The experimental specific gravity profiles indicate that Zangrando's redistribution method of establishing the pond using an injection diffusor resulted in entrainment of the pond brine from the lower level which in turn resulted in the reduced LCZ thickness with no gradient formation in the top layers of NCZ. This could
be corrected using fresh water scanning injection, surface flushing and cool brine injection into the LCZ so that the pond with design values of LCZ (1.9m), NCZ (1.3m) and UCZ (0.25m) has been developed.

Heat extraction does not affect the NCZ and UCZ specific gravity values but introduces some sort of stratification in the lower level of LCZ which disappears automatically before the next heat extraction. Cooled brine injection at the lower level of the LCZ is responsible for the stratification and once the pond gets heated up the specific gravity stratification disappears. The lower boundary moves towards the extraction diffuser during heat extraction.

The specific gravity profiles which are inherently flexible and spatially precise could be used to monitor long term mixing layer growth and instability formations. These instabilities such as increase of salinity in the UCZ, decrease of salinity in the LCZ, development of internal convecting layers in the NCZ, wind induced mixing, rain penetration mixing, heat extraction and reinjection disturbances tend to affect the zone thickness and zone boundaries and consequently the performance of the pond. Surface Hushing of UCZ, sail replenishment in the LCZ and gradient correction either by salt addition to the NCZ to remove local convective layers.

Increase of salinity in the UCZ, decrease of salinity in the LCZ and local convective layers which tend to destabilise the pond can all be detected from the specific gravity profiles, which skillfully applied either singly with suitable combination depending upon the situation correct the instabilities and control the boundary migration.
The corrective/control measures try to contain the movement of zone boundaries. In spite of the corrective operations the boundaries tend to move downwards. The NCZ thickness is not altered much, the variation lying within about ±0.1 m which may not affect the performance of the pond much.

During heat extraction, the lower boundary migrates to within about 0.1 or 0.05 towards the extraction diffuser level irrespective of the season. The upper zone boundary is affected by rain and moves downwards very much in the summer particularly when heat extraction is resorted to. Comparatively the migration of the zone boundaries are within the limits given by several investigators and hence the zones could be considered to be fairly stable.

The Newell and Boehm stability criterion has been satisfied for the entire one year period of operation of the pond which shows that the pond is stable. The stability is high when the temperature difference between the LCZ and UCZ is small. When the temperature difference is high $C/T$ tends to decrease to a value close to the minimum value for stability (i.e., $3.9 \times 10^{-3}$ Kg salt/Kg salt solution - °C). Salt addition to the LCZ to increase $AC$ or heat extraction to keep $AT$ at a suitable value or a combination of these can be adopted to achieve the stability condition which in turn means the pond is stable. The pond has been maintained stable all through the four seasons of a year.

The temperature profiles almost follow the same pattern as the specific gravity profiles. The temperature profiles show that in the initial stages, the gradient is formed up to some level in the NCZ depth where there is a maximum and this maximum moves down as heating process continues and when it reaches 1.55 m from
the top level corresponding to the lower boundary level, the gradient is completely formed and after that stage, the temperature at this level does not increase but the LCZ layers get heated up.

The optimum depth for maximum temperature attainment has been found to be 1.55m the same as that predicted for the NCZ-LCZ boundary by the modeling studies.

Once the steady state is reached the temperature and specific gravity profiles show close agreement in the location of the mixing layers. The zone boundary movements can be predicted from the temperature profiles also. The temperature profile show that once heat is extracted, the temperature of LCZ falls establishing some sort of temperature gradient/stratification in the LCZ which disappears before the heat extraction on the next day. This shows that the heat energy, is regained and nothing is drawn from heating up period stored energy and so the pond can be operated for a very long time.

The theory (using both BC and PP transmission relations) shows that there are two maxima in the NCZ layers one near the upper zone boundary and the second at the lower zone boundary and the second at illic lower /one boundary contrasting the experimental profiles. But theory shows that as the heating continues, the first maximum disappears and gradient is formed with the maximum temperature at the Lower Zone Boundary.
The time predicted by the theory for gradient formation is more or less the same as that obtained by experiment and theory and experiment give the same depth of 1.55m from top as the layer of the maximum temperature collection (LZB). Both theory and experiment predicts that the temperature of LCZ increases as time advances. Once the steady state is reached, the theoretical and experimental profiles are similar.

Experiments show that initially the temperature at the top of the LCZ is high and decreases towards the bottom and after the steady state gets uniformised. This behavior is not exhibited by the theoretical profiles.

The BC transmission relation gives temperatures which are 50% more than the experimental value whereas the PP relation leads to values which are just around 18% more than the experimental value. This indicate that the theory using the PP relation gives a more realistic picture of the pond situation.

Experimental studies show that during the initial heat-up period, the rate of heating in general, decreases as the temperature increases and at high temperatures it is very low (0.35°C/day at 70°C). Vagaries of climatic parameters, insolation and injection of low temperature brine for gradient correction and algal formation affect the rate of heating of the pond and some times the general trend is not followed.

Theory also predicts that the rate of heating decreases as the storage zone increases. However theory predicts higher rate of heating than that given by experiment. Use of PP transmission relation gives the rate of heating closer to the
measured values in the actual pond. This also indicates that the PP transmission relation gives a more realistic picture of the actual solar pond situation.

The rate of heating of the pond under heat extraction conditions at 70°C can be much greater than that at the initial heat-up period (at the same temperature). This may be due to the temperature inversion created in the LCZ facilitating greater heat energy reaching the LCZ.

The rate of heating of the pond under heat extraction condition, on an average, more or less matches the fall of temperature due to the heat extraction from the pond in a day. Nothing has been drawn from the stored energy of the pond. So the pond can be operated for a very long time.

The ground heat profile shows that the loss through ground conduction is low. When the heat extraction begins, the temperature initially falls and regains more or less to the original level subsequently.

Under no-heat extraction condition, the performance of the Pondicherry pond can be approximated to that of a flat plate collector with a value of &0.31 and flat plate loss co-efficient 0.96 W/m²°C.

With the designed heat extraction system, initially a heat energy recovery of around 100KWh and low heat extraction efficiency of only 4% could be obtained which could be
1) due to low flow rate of 8 lt/s which in turn could be attributed to the resistance offered by the pipe and 90° elbows and bends and gate valves in the pipelines and drop in pressure head experienced in the suction system, and

2) due to low temperature drop across the heat exchanger.

Using a modified Trombone cooler heat exchanger with 3 pipe lengths and arranging the remaining 3 lengths along a straight line on the ground, replacing the 90° elbows and bends by long bend flexible PVC tubes and reducing the number of gate valves and using conical collectors to collect and trickle water over the entire area of the pipes as a result the desired flow rate of 15 to 16 lt/s with a temperature drop of 8.5 to 9°C could be obtained.

The heat extraction efficiencies range from 17.5% to 19.5% for obtaining a heat output of 500 KWh or more showing that, comparatively, the pond is performing efficiently. For 86% of the days of a year, heat extraction can be done.

Comparing the theoretical predictions using the BC and PP transmission relations, it can be seen that the theoretical predictions using the PP transmission relation give a close approximation to the temperature history of the pond for the full one year period including the initial heat-up period, cooling period and heat extraction period showing that the PP transmission relation leads to a realistic prediction of the pond situation. So the PP transmission relation can be taken to be a close approximate relation for predicting the performance of the pond.
The study reveals that a full scale solar pond can be designed, constructed and successfully operated to suit the heat extraction requirement. The lining scheme developed for the containment of the pond brine makes the pond leak proof and stable and this scheme could be used for any pond site with high soil permeability. The innovative lowcost and simple in-pond saltdozer and heat extraction diffuser with foot valve coupling developed, makes the maintenance and establishment of the pond easier. The simple indegeneous lowcost design of the heat exchanger with minimized fluid friction accommodates different flowrates with optimum quenching for obtaining the desired heat output. The simple model presented helps in predicting the pond performance and fixing the zone thicknesses. An experimental transmission relation under clear pond conditions for the Pondicherry Pond has been obtained. Incorporating this Pondicherry Pond transmission relation in the model instead of the Bryant and Colbeck relation, results in a realistic prediction of the pond performance close to the experimentally observed performance.

Inclusion of wind induced mixing, rain penetration effects, movement of one boundaries, grid points in the UCZ and LCZ would have made the solution of the governing equations very difficult. Though every effort has been taken to maintain pond clarity, the pond became a little less transparent occasionally. The usage of pumps with optimum power for circulating the brine and cold water, instead of the available pumps in the market would have increased the net thermal output.