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Laboratory studies on dynamical processes in salinity-gradient solar pond

Xu, He, Ph.D.
The Ohio State University, 1990
LABORATORY STUDIES ON DYNAMICAL PROCESSES IN SALINITY-GRADIENT SOLAR POND

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy in the Graduate
School of the Ohio State University

by

He Xu, B.Sc., M.S.

*****

The Ohio State University
1990

Dissertation Committee:

Professor C. E. Nielsen
Professor R. L. Mills
Professor C. D. Andereck

Approved by

Carl E. Nielsen
Advisor
Department of Physics
To My Parents For Their Continued Support And Encouragement
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VITA

October 10, 1951 .................................. Born – Beijing, China

1976 .................................. B.Sc., Beijing Teachers College

1976 – 1982 .................................. Instructor, Department of Physics,
                                       Beijing Teachers College,
                                       Beijing, China

1982 – present .................................. Teaching Associate, Department of
                                       Physics, The Ohio State University,
                                       Columbus, Ohio

1985 .................................. M.S., The Ohio State University,

PUBLICATIONS


FIELD OF STUDY

Experimental Fluid Dynamics
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CHAPTER I

Introduction

1.1 Basic Concepts of Salinity-Gradient Solar Ponds

A salinity-gradient solar pond is a large body of water that normally consists of three distinct zones: a relatively thin surface zone on top, a nonconvective gradient zone beneath it, and a lower storage zone on bottom. Usually the surface zone and lower storage zone are convective and maintained homogeneous both in salinity and temperature. A schematic of the three zone configuration of solar pond is presented in Figure 1.1.

The nonconvective gradient zone is the core region in the salinity-gradient solar pond in which the salinity gradient is obtained by dissolving salt, usually sodium chloride, into the water at increasing concentrations. If the salinity gradient is large enough, there will be no convective motion when heat is absorbed on the bottom, because the hotter saltier water at the bottom of the gradient zone will be denser than the colder less salty water above it. Since water is transparent to visible light but opaque to infrared radiation, energy in the form of sunlight that reaches the lower storage zone is absorbed there
Figure 1.1: A schematic of the three zone configuration of solar pond. The solid curve in this figure presents the typical salinity distribution in solar ponds.
and can be transferred only by heat conduction. The thermal conductivity of water is moderately low, and if the gradient zone is relatively thick, heat escape upward from the storage zone will be very slow. Therefore the non-convective gradient zone acts as a transparent insulation that floats over the lower storage zone maintained at highest concentration and highest temperature. The optimum gradient zone thickness depends on the desired storage temperature, optical properties and thermal properties of salt solution. The typical gradient zone thickness is in the order of 1 m.

Since the salinity gradient solar pond can be thought of as a combination of solar collector and thermal storage device, it has received attention as a low cost alternative energy source for a variety of low temperature thermal applications. The state of knowledge of the solar pond including its history, principles, processes and applications has been reviewed extensively by Hull, Nielsen and Golding [1], Nielsen [2] [3], Hull and Nielsen [4], Tabor [5], Tabor and Weinberger [6]. While many solar ponds have been built and operated throughout the world during these years, and many aspects of solar pond design and operation are well understood, there are still many basic questions of the dynamic processes in solar pond which have not been answered yet. Among these questions, there are three major ones which directly effect the thermal performance of solar ponds; they are the stability of gradient zone, the movement of gradient-convective boundaries and the surface zone creation and growth.
1.2 Observations of Internal Gradient Breakdown in Solar Ponds

One of the most important questions concerning the dynamic processes which influence the performance of solar pond is whether the gradient zone is stable. Since the absorption of solar energy results in a temperature increasing with depth, the salinity must also increase with depth to overcome the destabilizing effect of temperature gradient. Under some conditions, the potential energy stored in the temperature gradient can be released by small perturbations, and this release results in mixing. Therefore, the stability of the gradient zone is a dynamic condition, requiring a net positive density distribution as a function of depth.

It has been observed in many solar ponds that if the stabilizing salinity gradient is not strong enough to balance the effect of the destabilizing temperature gradient, instability occurs and internal convective layers are formed. These internal convective layers reduce the total thickness of the non-convective region and sometimes even destroy the whole gradient zone. One observation of gradient instability was made by Nielsen in the FSR solar pond at The Ohio State University, Columbus, Ohio. This pond was built in 1975 and is still in operation [7]. The gradient of the pond was observed to breakdown during the summer of 1980. It was found that the instability developed near the middle of the gradient zone and propagated to become a succession of convective zones encompassing a thickness of about 55cm of
the gradient zone [8]. Zangrando [9] studied the stability of the gradient zone under variable gradient conditions in an experimental solar pond. In these experiments, instability resulted in the formation of one or more internal convective zones located about the weakest points in the salinity gradient. Similar observations have also been obtained by Swift in the El Paso solar pond [10] and by Betbeze in the TVA solar pond at Chattanooga, Tennessee [11]. All these observations show that the existence of internal convection zones resulting from internal gradient instability reduces the efficiency of the pond thermal performance substantially. In the TVA pond, after the internal instability occurred, the temperature in the lower storage zone decreased approximately 20°C just in 20 days.

Since maintaining a stable gradient zone is essential for solar pond operation, it is important to understand the dynamic processes of the gradient breakdown and to provide a method for evaluating the stability of the gradient zone. The previous studies on the dynamic processes of the internal instability in solar ponds have been reviewed by Nielsen [1] [3]. In those studies, the results from the analysis of double-diffusive convection system have been applied to investigate the stability criterion in solar pond [12] [13]. However, many aspects concerning the nature of the internal instability still have not been extensively studied especially in the comparison of the theoretical results with the experimental observations, and also a convenient procedure for predicting the gradient instability in solar pond still has not been developed for practical uses.
1.3 Behavior of Boundaries Between Gradient Zone and Convective Zones

Another most important problem in the operation and maintenance of a salinity gradient solar pond is the stability of boundaries between gradient zone and convective zones. It is very common in operating solar ponds that the gradient zone is shrinking gradually as the result of growing in thickness of surface convective zone and lower storage zone unless preventive or corrective measures are taken. This kind of gradient-convective boundary movement is undesirable since too thin a gradient zone will produce larger heat losses from the lower storage zone and reduce the pond thermal efficiency.

It is observed in laboratory tanks and in outside solar ponds that the boundary between convective zone and gradient zone is characterized by a relatively sharp interface at a certain level in which the gradient changes rather sharply from a non-zero value to zero. If the tendency of diffusion to enlarge the gradient zone can balance the strength of erosive convection at the gradient-convective zone boundary, the boundary can be maintained stationary. A correlation of temperature gradient and salinity gradient near the boundary for boundary equilibrium has been determined by Nielsen experimentally [14] [15] from observations on laboratory tanks and outside solar ponds. This correlation has been confirmed by the observations of gradient zone behavior in the ANL pond [16] and in the pond at Miamisburg, Ohio [17], although the physical processes involved in the balance of boundary
movement are still not well known.

Some information about the structure of gradient-convective boundaries is provided by Kamal and Nielsen [18] who made very high resolution temperature measurements in laboratory tanks. In their experiment, the varying shape of temperature distribution and temperature fluctuations of tenths of a degree C were observed near the gradient-convective boundaries. These results suggest that the generation and releasing of thermal plumes at boundary layer may play an important role in the boundary behavior. A rich variety of dynamic processes associated with the zone boundary behavior has been observed in a number of other laboratory tank studies [19] [20] [21] [22] [23].

Based on these experimental observations, Nielsen [3] has proposed a boundary layer model to qualitatively explain the structure between gradient zone and convective zone in a solar pond. A similar model had been applied earlier to predict the erosion and growth rate of diffusion interfaces by Witte and Newell [24]. Meanwhile, some other investigators have studied the entrainment of kinetic energy at gradient-convective zone boundaries [25] [26] [27]. Although much progress has been made in recent years, there are still many questions such as what is the mechanism of the heat and mass transfer through the gradient-convective boundary and what kind of dynamic processes are involved in the balance of the transition region. To answer these questions, more research works both experimental and theoretical are called for.
1.4 Observations of Surface Convection Produced by Surface Temperature Cycling

It is always observed in operating solar ponds that there is a surface convective zone on the top of the ponds [2]. The temperature of surface convective zone is near that of the ambient air and the surface thickness is in the range of 20cm to 40cm typically. This surface convective zone is undesirable since it is not effective as insulation like the gradient zone or as thermal storage like the lower convective zone, and it does decrease the insolation reaching deeper layers.

Since the surface convective zone is influenced by external effects, the dynamic processes involved in the surface behavior are very complicated. It has been found that the most important erosive effects causing the surface zone creation and growth are wind mixing, evaporation and surface temperature cycling. To reduce the wind effect, floating plastic nets, floating plastic pipe and some other localized wave barriers have been used in operating solar pond. However, at present there is not enough information for deciding what type of surface barrier will be required at a given site [1]. It has been observed that the salinity increases at the surface due to the removal of water by evaporation. The salinity increasing on top has been considered as an erosive effect which produces or enhances the surface convection. However, this salt deposit phenomena is very complicated, and sometimes it performs the opposite effect. Golding and Nielsen [28] have observed that following
periods of surface evaporation, the salinity gradient was extended upward for
distances to 10cm.

The temperature cycling on the surface is another more complicated and
less understood process on surface convective zone creation and growth.
The effect of surface temperature cycling has been described qualitatively
by Nielsen [2] as the origin of the surface convection if the wind mixing is
excluded. For the growing process, Nielsen [1] pointed out that a non-steady
thermal convection produced by temperature cycling on surface is more ero­
sive than steady thermal convection associated with the same average heat
transfer rate because of a nonlinearity in the relation between heat trans­
fer and erosion. It has been also predicted by other theoretical studies that
cooling on the surface may produce surface convection [29] and the effect of
surface temperature cycling may be more important than the wind effect in
some circumstances [30].

Experimentally, there are various pieces of evidence [31] [32] [33] showing
the importance of non-steady thermal convection on the erosion of the gra­
dient. However, it is still not well known what is the role of the temperature
cycling acting on the surface individually because of the difficulty to separate
the temperature cycling from the other two major effects.

1.5 Objectives and Scope of the Present Studies

As discussed above, the dynamic processes which involve internal gradient
stability, behavior of boundaries between gradient zone and convective zones
and surface zone creation and growth have strong influence on the thermal performance of solar pond. In order to obtain an improved understanding of these dynamic processes, experimental studies have been conducted in a laboratory thermohaline system which is similar to solar ponds. Emphasis is on laboratory modeling of these processes under carefully controlled conditions. Based on the experimental results, physical mechanisms of these processes are discussed.

The objectives of this study are the following:

1. (a) To investigate the conditions under which instability initiates within the gradient zone. Emphasis is on the measurement of temperature and salinity profiles in gradient zone successively and on the measurement of temperature oscillation at the position where the gradient breakdown occurs. (b) To further explore the oscillatory nature of the development of internal instability in the gradient zone of the solar pond. (c) To formulate a practical procedure for evaluating the internal stability of the gradient zone in solar ponds.

2. (a) To investigate the temperature and salinity fluctuations at the boundary between gradient zone and convective zone. Emphasis is on the simultaneous measurements of temperature and salinity fluctuations, on the fine structure of temperature and salinity profiles around the boundary and on simultaneous measurement of temperature fluctuations at different levels. (b) To obtain the dynamical structure of boundary layers between gradient zone and convective zones and to understand the different physical mecha-
nisms involved in boundary behaviors.

3. (a) To investigate the characteristics of temperature variation near the surface and the mixing processes produced by surface temperature cycling. Emphasis is on the control of the experimental conditions, the measurements of temperature and temperature gradient near the surface varying with time and the observations of mixing occurrence. (b) To understand when and how the surface mixing occurs and to explain the mechanism of the surface temperature cycling produced mixing process. (c) To investigate the characteristics and behavior of surface-gradient zone boundary movement induced by surface temperature cycling and to further understand the nonlinearity in the relation between heat transfer and erosion on the boundary movement.
References


CHAPTER II

Test Apparatus and Experimental Methods

2.1 Introduction

In this chapter the laboratory tank apparatus used throughout this dissertation and the general experimental conditions achieved during entire experiments are presented in detail first. Then the instruments and the measurement methods for the temperature and salinity measurements are described with detailed discussions of the corrections of data for sensor time constant.

The basic design consideration in the construction of the laboratory tank apparatus was to provide a reasonable simulation of larger ponds and to achieve a horizontal homogeneity of all fluid thermodynamical properties in the tank. Geometrically, a circular shape with a vertical wall is the most symmetric design for the pond. In our tank apparatus, a cylindrical tank with an appropriate width to height ratio was chosen as a container and electrical heaters at the bottom were so arranged as to provide a uniform horizontal heat source. Thermally, it is important to avoid any lateral heat flux which can generate mean flow circulation and even destabilize vertical salt distri-
bution [1] [2]. To eliminate the lateral heat flux, an electrical sidewall heat loss control device was designed and used in our tank apparatus.

In the design of surface heating/cooling system, the air which smoothly blew across the water surface was used as the heat transfer medium. The flow rate of the air was controlled well enough that no mechanical disturbance of any significance was detected during any experiment.

A movable diffuser designed for injection was used for establishing a NaCl salinity gradient in the tank and for modifying the salinity profiles to reach the desired gradient condition in different experiments. The salinity redistribution method first introduced by Zangrando [3] which was successfully performed in several solar pond experiments was used as the standard filling procedure in our experiments. The same injection principle was also used for the salinity profile modifications.

A surface wash device, in which flow rate can be controlled precisely, was designed to balance the surface water evaporation and the salt transported into the surface. The surface wash maintained a two zone configuration, gradient zone and lower convective zone, in the experimental tank during all the experiments except for a short period of time immediately after very strong surface heating/cooling cycling in which a surface convective zone was produced.

It is important to obtain a high spatial resolution on the temperature measurements for the purpose of stability analysis which requires a fine structure of the temperature distribution. In order to obtain the temperature fluctu-
tions in and near the interface between gradient and convective zones, a fast frequency response of the measurement probes is also necessary. Based on these considerations, thermocouples are used as the temperature sensors for all the temperature measurements in our experiments.

A conductivity probe was developed to obtain a instantaneous salinity profile accompanied with the temperature measurement simultaneously. The conductivity probe was also used for the time series salinity measurement in the study of the boundary behaviors. Another method for the salinity measurement is the sample weighing. In this method, samples were taken and weighed to obtain an accurate salinity distribution that was used as the calibration standard for the conductivity probe.

The instantaneous temperature and salinity profiles were obtained by the means of scan. Data were sampled by a data logger which was controlled by a computer. The time interval between two samplings gave an accurate spacing in depth if the scan speed was well defined. The high resolution and high accuracy voltmeters were used for the temperature fluctuation measurements. A lock-in amplifier was used in the circuit for the conductivity measurements, which was vary reliable during the experiments. All the data were collected by a data logger and sent to the computer storage for further data analysis.

Sensors used for measuring temperature and salinity commonly do not respond to environmental changes in negligible time. The sensors can be characterized by their response functions, which must be known if the actual environmental values of changing quantities are to be found from the outputs
of the sensors. However a sensor response normally approaches the environmental value after a sufficiently long time that depends on the nature of the sensor, so the deviations of sensor readings from environmental values are important only when quantities to be measured are time-varying at a rate comparable with or exceeding the rate of response of the sensors.

During our experimental measurements of brine temperature and conductivity, we have found that a sensor response time of only a few seconds may significantly affect the measured values, especially in short range scans through the interface between gradient and convective zones and in the observation of temperature and salinity fluctuations in and near the interface region.

The dynamic responses of measuring instruments have been discussed in the literature [4] [5] [6] [7], and the effect of instrument characteristics on the response obtained has been described. Also, an electrical compensation procedure for use in measurement of a step change in environmental temperature has been given [6] [8]. However, we have not found any discussion of a general procedure for obtaining the environmental value from the sensor response when the time variation is arbitrary, or when it is of the special form that we encounter when moving a temperature or salinity probe up and down into or through a gradient region.

In this chapter we point out that if the sensor response function is sufficiently well represented by an exponential approach to equilibrium with a characteristic time constant $\tau$ then there exists a very simple means of ob-
taining the true environmental value from the instantaneous sensor response at any instant combined with the time rate of change of the sensor response evaluated at that instant.

The result stated above is derived and applied for particular cases of short range scans. Then the case of more or less random fluctuations is discussed, using as examples the observed temperature fluctuations in and near the interface region, and also a procedure for evaluating the time constant both for a stationary probe and for a moving probe is presented.

2.2 Laboratory Tank Apparatus

2.2.1 Experimental Tank

All the experiments to be described in this dissertation were performed in a laboratory tank. The laboratory tank apparatus consisted of a cylindrical plastic tank, sidewall heat loss control device, and a heating plate at the bottom. The sketch of the laboratory tank apparatus is shown in Figure 2.1.

The inner diameter of the experimental tank was 0.75m and the depth of the tank was 1.2m. To achieve the best insulation, the plastic tank was surrounded by a thin steel guard cylinder and insulated by 8cm of styrofoam in between. On the guard cylinder, six groups of heaters, 16 in each group, were installed at six different levels; see Figure 2.1. Outside of the guard cylinder, a layer of 2.5cm thick fiberglass insulation was used to reduce the influence of environmental temperature variations.
Figure 2.1: The sketch of the experimental tank apparatus. All units in this figure are in centimeters.
The base of the tank was a 2\,mm thick aluminum plate which was placed beneath the tank with 7 electrical heaters mounted to the bottom of it. These heating elements were so arranged as to provide approximately uniform heating over the entire base. Heat supplied to the tank can be varied by adjusting the input voltage. The range of the input voltage was from 0\,V to 110\,V which corresponds to the power range from 0\,W to 140\,W. The sketch of the heating plate and the diagram of the electrical circuit of the bottom heating supply are shown in Figure 2.2 (a) and Figure 2.2 (b) respectively. To avoid heat loss into the ground, a 30\,cm thick styrofoam insulation was used in between the metal heating base and the ground.

**2.2.2 Electrical Side Wall Heat Loss Control**

Besides the regular side wall insulation, computer controlled electrical heaters on the guard cylinder were used to eliminate any lateral heat flux. In principle, if the temperature difference between the inside fluid and the guard cylinder is kept at zero at any level, there will be no lateral heat flux though the tank, and an ideal experimental condition can be reached.

In our design, six pairs of thermocouples were mounted on the outside of the plastic tank and on the guard cylinder at the same six levels as the heaters to monitor the temperature difference between the tank and the guard cylinder. The signals of temperature difference were sent to a data logger coupled to a desk top computer. The computer program checked the temperature differences at each level. If the temperature difference at
Figure 2.2: (a) The diagram of the arrangement of heating elements on the heating plate. (b) The diagram of the electrical circuit of the bottom heating supply in which seven 10Ω resistors are used as the heating elements and a variable transformer is used to adjust the heating power.
a certain level was larger than a predetermined value, $-0.4^\circ C$ typically, the computer sent a command to an actuator, and the main switch in power circuit for the heaters in that level would be closed to start heating. If the temperature difference was smaller than a certain value, $-0.2^\circ C$ typically, the main switch would be opened to stop heating.

The average temperature differences between the tank side wall and the guard cylinder at each level was controlled to less than $\pm 0.5^\circ C$ during all experiments. In contrast, the average temperature difference between the heated fluid inside and the ambient air outside was about $10^\circ C$. Therefore, $8cm$ insulation in our laboratory tank apparatus was equivalent to $160cm$ thick insulation by using the ordinary method. The energy lost through the tank side wall was estimated to be less than $0.1W/m^2$. This amount of heat loss was $0.25\%$ of the average heating rate, which was $40W/m^2$ in general, and was negligible.

In addition, a set of thermocouples was used to examine the horizontal temperature difference between the tank side wall and the fluid inside. Since this temperature difference was too small to detect, it was experimentally verified that an one dimensional experimental condition was achieved in our laboratory tank apparatus. The detailed electrical diagram and the computer program of the side wall temperature difference control are shown in Appendix A.
2.2.3 Surface Heating and Cooling System

In our test apparatus, a surface heating/cooling system was designed to simulate the temperature variation on the surface of the solar pond. This system consisted of a heating element, a cooling element, a heating/cooling path switch, and an air flow distributor. The air which blew over the water surface served as the heat transfer medium. The main consideration of the heating/cooling system design is to avoid any wind mixing on the surface. This condition was achieved in our system. The sketch of the heating-cooling system is shown in Figure 2.3.

A 4cm inside diameter ceramic insulated steel tube wrapped with a 7Ω resistance wire was used as the heating element, which was connected to AC power line through a variable transformer. When the air flowed through the inside of the tube, it was heated by dissipating the electrical power which was adjusted from 100W to 1000W depending upon the requirement of the output air temperature.

As a cooling element, a refrigerator kept a constant low temperature, \(-15°C\), in a thermostated cooling bath. A metal grid was placed in the bath to enhance the heat exchange and maintain the temperature difference between the incoming and outgoing air greater than 30°C.

The heating and cooling elements were connected in series. During the cooling cycle the heater was off and acted just as a piece of tube. The air flow driven by an electrical blower, 10cm in wheel size, through the heating/cooling switch box entered the cooling bath. Then the heat was extracted
Figure 2.3: The schematic of the heating/colling, surface washing and sample taking systems.
and the cold air was sent to the flow distributor on the top of the tank. After exchanging the heat with the surface water, the warmed air returned to the driving fan and completed the cooling cycle. The heating cycle was the same as the cooling cycle except that the air valve box bypassed the cooling bath and the heater was turned on. The air hoses between each element were 4.5cm in diameter and thickly wrapped with rubber foam.

The function of the air flow distributor was to unify and smooth the air flow on the water surface. It was specially designed with a double layered wooden cover on the top of the tank; see Figure 2.3. The height between the water surface and the flow distributor was 12cm. Within this space, the air flow speed was so carefully controlled that no wind disturbance of any significance was detected. Since there was not any recognizable surface mixing by the air blowing over the water surface, it was experimentally verified that the wind effect can be neglected in our laboratory experiments.

2.3 Injection Method and Surface Wash Process

2.3.1 Injection Apparatus and Gradient Establishment

In our experiment, the injection method was used to establish the salinity gradient and to modify the gradient profile in the tank. The injection was made by a diffuser which is 7cm in diameter and 0.5mm in gap, showing in Figure 2.4. The position of the diffuser was adjustable for meeting the injection requirement. The fluid with predetermined salinity was pumped
Figure 2.4: The sketch of the diffuser which is used for the injection in the tank experiments.
through the diffuser which permitted discharge only in the horizontal plane. To control the injection rate, a 0 to $26 \, ml/sec$ metering pump was used in the injection setup for the gradient modification.

The salinity gradient was established in the laboratory tank by using the salinity redistribution technique [3]. The procedure of this technique consists of partially filling the tank with high salinity NaCl solution. Fresh water is then injected through the diffuser which is immersed in the upper portion of the existing solution. The brine above the diffuser will be progressively diluted while the diffuser, as well as the water level, rises. Finally, the diffuser reaches the water surface at the predetermined ending level.

As an example in our experiments, a two zone configuration, a gradient zone and a lower convective zone, was obtained by the salinity redistribution technique. The diffuser was initially at the height $z = 70cm$ (measured from the bottom of the tank) which determined the thickness of the lower convective layer. The NaCl solution with 11.3% salinity was filled up to the level of $z = 87cm$. Then fresh water was injected. By raising the diffuser in increments of $2cm$ as the water surface moved vertically upward $1cm$, a linear salinity distribution was obtained. The injection procedure was finished when the water surface reached the level of the tank outlet which was positioned at $z = 104cm$. The thickness of the gradient zone was $34cm$ in which a constant salinity gradient, $32.4%/m$, was through the whole region. The designed salinity profile and the profile obtained by the redistribution technique are shown in Figure 2.5.
Figure 2.5: Two zone configuration in the experimental tank obtained by the salinity redistribution technique. The solid line is the expected linear salinity distribution of the gradient zone, and the marked salinity distribution is the measurement taken 12 hours after the gradient established.
This injection setup was also used to make salinity gradient modifications [9], which based on the same injection principle as the salinity redistribution technique, in some experiment runs. Detailed discussions of the salinity gradient modification procedures are given in Appendix B.

2.3.2 Surface Wash Process

During the experiment, evaporation occurred and salt was transported into the surface. In order to maintain a certain salinity profile through the entire experiment, a continued supply of fresh water for surface wash is needed.

In our surface washing system, two pieces of copper capillary tube, one which was the incoming tube connected with tap water and another which was the outgoing tube to the tank with a narrow outlet floating on the water surface, were used to reduce the water pressure and control the flow. Both tubes were $7m$ long and $1.5mm$ in diameter and connected to a $1cm$ diameter glass cross which served as a reservoir for flow control. The upper end of the glass connector was always open and maintained the same pressure as the atmosphere. Since raising or lowering the glass connector caused the relative pressure between the connector and the water outlet to change, the flow rate can be set very accurately by adjusting the relative position of the connector during all the experiments. The diagram of the surface washing system is shown in Figure 2.3.

Since the typical salinity gradient in the experimental tank was $20%/m$ and the salt diffusivity for NaCl solution is about $2 \times 10^{-6} m^2/sec$, the average
salt transported into the surface was 18 grams per day approximately. To maintain a surface salinity of less than 0.6 % and a surface convective zone of no significance, the surface wash flow rate was set at 9 liters per day during the entire experiment.

Since the surface washing rate was very slow and the copper capillary tubes especially the piece of approximately 10cm long near the outlet lying on the water surface served as a good heat exchanger, the temperature difference between the washing water and the surface water was less than 1°C typically and the heat carried out by the surface wash was less than 0.4W. In comparison to the total heat flux through the surface that was 20W in general, the effect of surface wash in the heat balance can be neglected.

2.4 Temperature and Salinity Measurements

2.4.1 Temperature Measurement

In our experiment, copper-constantan T curve thermocouple was used as the temperature sensor. The thermocouple wire is 0.255mm in diameter and silver soldered to form a measurement junction. The size of the sensing junction is less than .6mm which gives a very good spatial resolution and an approximately 2.5sec time constant. Although the sensor size is already very small, its dynamic response on measurements still can not be negligible in certain experiments. The determination of the time constant and the compensation of sensor response will be discussed in Section 2.5 in detail.
A vacuum bottle filled with enough cracked ice and water served as the cold junction container. The cold junction of the thermocouple is connected with a large piece of metal to increase the heat capacity of the cold junction and further minimize any temperature fluctuations at cold end. A long time constant of the cold junction is special useful for obtaining reliable data from the observations of the boundary behaviors.

A Keithley Model 181 digital nanovoltmeter was used to measure the thermoelectrical potential from the thermocouples. The amplified analog signal was then sent to the data logger. The sensitivity of the nanovoltmeter is $10^{-8} \text{V}$ on $2\text{mV}$ range and the display resolution is $6\frac{1}{2}$ digits. Combining the temperature sensor and this measurement instrument together, a sensitivity of $1/250^\circ\text{C}$ on the temperature measurements can be achieved. Absolute uncertainty for copper-constantan thermocouples is $\sim 0.5^\circ\text{C}$; this uncertainty is not important in the present work, which is concerned primarily with temperature fluctuations.

### 2.4.2 Salinity Measurement

There are two basic methods which were used to measure the salinity profiles and salinity fluctuations in the tank experiments. The first method is the sample weighing method. By using a travelable sample taking device, a series of samples at different positions can be taken and then weighed by a Mettler H10 digital analytical balance which gives 6 significant figures in weight. The second method is the conductivity measurement. The conductivity probe
gives direct electric signal which can represent the salinity of the solution by using a certain calibration procedure. Because it may make a continuing measurement, the conductivity probe was also used to measure the salinity fluctuations and the fine structure of the salinity profiles.

The sample taking device consists of a manual traversing mechanism and a fluid sample withdrawal tube; see Figure 2.3. A slide block on a vertical track can be moved up and down. The supporter of the sample withdrawal tube was mounted on the slide block. The end of the sample withdrawal tube is a T-shaped sampler in which inlet gap is 1mm. The position of the sampler is determined by a meterstick fixed on the track. The spatial uncertainty of the measurement is less than 2mm.

The salinity of the samples was determined by weight analysis using a 25ml pycnometer. A pycnometer is a special flask that can be refilled to produce samples which contain the same volume. These samples can be weighed and compared to a sample of distilled water at the same temperature to obtain the specific gravity. Knowing the specific gravity and standard local temperature, the salinity in percent by weight can be calculated by using the conversion formula given in Appendix C.

For the conductivity measurements, a four wire conductivity probe which is based upon Nielsen’s design [10] was used. In this design, an electric field is produced by a 1000Hz current of constant amplitude flowing through the outer field electrodes and sensed by the inner testing electrodes. The probe was constructed using four pieces of 0.5mm diameter platinum wire and a
leak proof seal. All these four electrodes are parallel and connected to a conduction cable. The connections were sealed with silicone rubber which made the shape of the probe as a rectangle. The protruding platinum wire ends are 5mm long and 2mm apart.

The 1000Hz AC input signal to the outer electrodes is provided by the internal signal generator of PNC model 221 lock-in amplifier. A 10KΩ resistor in input circuit reduces the current a great deal and makes the electric current between the outer electrodes nearly constant, less than 5\% current variation in amplitude as the salinity of solution changing from 0\% to 15\%. The resulting AC signal from the inner electrodes is stepped up with a 1000Hz single pass filter transformer and input to the lock-in amplifier. The transformer also makes the inner electrodes floating from the common ground. The lock-in amplifier only amplify 1000Hz signal and avoid any noises induced from the measurement environment. During the experiments, the gain of the lock-in amplifier was adjusted so that the maximum output signal was 2V. This signal was then sent to a Keithley model 177 voltmeter which converted the AC signal to DC signal for data logging. The electric diagram showing the circuit of the conductivity measurement is shown in Appendix D.

The conductivity of salt water depends on both the concentration of salt and the temperature of the solution. In order to obtain a accurate conversion from conductivity to salinity, frequent calibrations of the conductivity probe are needed. A regular sample set was taken once a week though all the experiments. The samples also were taken before and after each experiment
run. Since the temperature profiles did not change vary much during a certain period of time, the salinity obtained by the sample weighing can serve as a standard for calibrating the conductivity profile measured at the same time as the sample withdrawing and this calibration can be used throughout the time a certain experiment run conducted. The general form of the conversion formula between conductivity measurement and salinity is

\[ S = A C^B \]

where, \( S \) is salinity in \%, \( C \) is electrical signal, in volts, from conductivity probe. \( A \) and \( B \) are calibration parameters which can be determined by the curve fitting procedure. The typical values for \( A \) and \( B \) are 1.6 and 0.95 respectively and the correlations of the converted value and the true value are always greater than 0.99.

2.4.3 Scan and Data Acquisition

The instantaneous temperature and salinity profiles were obtained by using a motor driven probe raising and lowering device. This device was constructed by a reversible synchronous motor coupled with a set of speed reducing gears at a 5 to 1 ratio to drive a 5cm diameter drum which winds and unwinds fishing line connected to the temperature and salinity probes.

The moving speed of the probes can be adjusted by changing gears or changing the size of the driving pulley. If the scan is too slow, it will take a long time to obtain the whole set of measurements and they can not give reasonable instantaneous profiles especially for a long scan distance. If the
scan speed is too fast, not only it will cause fluid turbulence, but also the
effect of the time constant of the probes will induce a great deal of measure­
ment error. The scan speed we used in most of our experiments was set at
\(12 \text{ cm/min}\).

The driving device is controlled by a HP 85 computer which starts the
scan, reverses the probe moving direction and runs a sampling routine as
the probes are moving. A limit switch, which is active by a threaded block
moving along a threaded rod driven by the same motor as the scanner, is
mounted at the starting position to double ensure each scan started at the
same initial position although the driving device is started and stopped by
the computer. Since the starting position is very accurate for each run and
the scan speed is very steady, the position of each sampling can be deter­
mined by counting the moving time of the probes. The maximum computer
sampling speed is 0.5 second per reading which corresponds to \(1 \text{ mm}\) mini­
mum sampling spatial interval at the \(12 \text{ cm/min}\) scan speed. The detailed
scan control electric diagram and the sketch of the scan driving device are
shown in Appendix E.

The data acquisition and control system consists of a Hewlett Packard
3974A data acquisition/control unit, a Hewlett Packard 85 desk top com­
puter, a side wall temperature difference control unit and a scan control
unit. The block-type diagram showing the relations between each unit is
shown in Figure 2.6.
Figure 2.6: The block diagram of the data acquisition and control system.
The 3974A data acquisition/control unit has a 20 channel DC voltmeter with 1 microvolt resolution at 0.1V range and a 16 channel actuator with 16 mercury wetted form C SPDT relays in which switches can be individually closed. The HP-85 desk top computer has 64k bytes memory and a built in tape recorder with 210k bytes magnetic tape cartridge capacity. The HP-85 computer communicates with the data acquisition/control unit through an HP-IB interface.

For temperature and salinity scans, the computer sends commands to the actuator at pre-determined times. The actuator controls the driving device to start the scan. At the same time, the computer controls the data logger to collect the analog voltages from each of the measurement devices and converts them to digital signals which are addressed to the computer and stored on magnetic tape by the computer for further data analysis. The computer program of the scan control and the data collection are shown in appendix F.

2.5 Correction of Data for Sensor Time Constant

2.5.1 Dynamic Response of Measurement Probes and Compensation Procedure

A differential equation that may be used to describe approximately the dynamic response of temperature measurement probes such as thermocouples can be set up by using the law of energy conservation and Newton's law of
cooling, which linearly approximates heat transfer rate as proportional to temperature difference.

If heat is added to the probe at the rate $dH_p/\text{d}t$, the temperature increases at a rate depending inversely on the heat capacity as expressed in the equation $MC\text{d}T/\text{d}t = dH_p/\text{d}t$, $M$ being the probe mass and $C$ the mean probe specific heat. Taking the rate of heat addition to the probe as proportional to the difference between environmental temperature $G$ and probe temperature $T$, we have $dH_p/\text{d}t = Ah_e(G - T)$, in which $A$ is the surface area of the probe and $h_e$ is the effective surface heat-transfer coefficient. Eliminating $dH_p/\text{d}t$ we obtain

$$MC \frac{\text{d}T}{\text{d}t} = Ah_e(G - T). \quad (2.1)$$

In general $G$ and $T$ are functions both of time $t$ and of vertical coordinate $z$. However when a sequence of measurements is specified the trajectory is specified, so that $z$ is known as $z(t)$ and $G$ and $T$ can be expressed as functions of the single variable $t$.

We may define $\tau \equiv MC/Ah_e$ and write the differential equation in the form

$$\frac{dT}{dt} = -\frac{1}{\tau}(T - G(t)) \quad (2.2)$$

which has the solution

$$T = e^{-t/\tau}\left[\frac{1}{\tau} \int G(t)e^{t/\tau}dt + \text{Const.}\right]. \quad (2.3)$$

This solution represents the familiar exponential decay behavior with a time
constant $\tau$, except for the modification caused by varying environmental $G(t)$.

In the case of the conductivity measurement, the dynamic response of our conductivity probe can be described by the same type of equation although the physical process is entirely different from that of the thermocouple and we have

$$\frac{dS}{dt} = -\frac{1}{\tau_s}(S - F(t)) \tag{2.4}$$

where $\tau_s$ is the time constant of the conductivity probe, $S$ is the probe response and $F(t)$ is the environmental value of the conductivity.

The effect of the response time of the probes in the temperature and salinity measurements can be compensated during the data analysis by using Equation 2.2 and Equation 2.4 written so as to give $G(t)$ and $F(t)$ explicitly. For example, in temperature measurement, if the measured value $T(t)$, is known, and if the $\tau$ is known, the true environmental value $G(t)$ can be written as a function of $T(t)$

$$G(t) = T(t) + \tau \frac{dT(t)}{dt}. \tag{2.5}$$

This result is perfectly general and holds for any physically realizable function $G(t)$ which is necessarily continuous because the temperature is continuous everywhere in the fluid.

Since measurements commonly consist of a series of discrete values, it is useful to write the above equation as a finite difference equation,

$$G_i = T_i + \tau \frac{(T_{i+1} - T_{i-1})}{2\Delta t}. \tag{2.6}$$
where $T_i$ is the measured temperature of the probe and $G_i$ is the calculated estimate of true environmental temperature at each measurement time. The same procedure can also be used for the salinity measurement compensation using the appropriate time constant $\tau_s$.

Equation 2.6 will not contain a very good estimate of the slope at $T_i$ if the rate of change of the slope of $T$ varies significantly between $T_{i-1}$ and $T_{i+1}$. A variant of Equation 2.6 that uses adjacent points to evaluate the slope is

$$G_{i+1/2} = \frac{T_{i+1} + T_i}{2} + \tau \frac{T_{i+1} - T_i}{\Delta t}.$$

This expression, which gives corrected values $G_{i+1/2}$ time shifted by $\Delta t/2$ to points midway between $t_i$ and $t_{i+1}$, is the one we have used in the correction calculations presented in Figures 2.8 and 2.10. In Figure 2.11 there is an additional smoothing introduced by calculating first the new set of values $T_i' = (T_{i+1} + T_i)/2$ to use in Equation 2.7, and the additional time shift of $\Delta t/2$ thus introduced makes the total time shift in Figure 2.11 equal to $\Delta t$.

The above discussion gives a general procedure for the time response compensation of the measurement probes. This compensation method is valid in any case of temperature and salinity measurements in our experiments although different measurement environments may be involved. The usefulness of this method is illustrated in the following sections.

2.5.2 Temperature and Conductivity Scan

There are two basic kinds of change the probe may experience in the scan process: (a) there is a sharp change in gradient when the probe moves through
the interface between a convective zone and a gradient zone; (b) there is a nearly constant rate of change when the probe travels in a gradient zone.

In the case of a temperature scan for instance, suppose that the thermocouple begins to move from the position \( a \) in the lower convective zone in which the temperature is a constant \( T_c \) and moves up continuously. When the probe reaches the gradient zone at the position \( b \), the temperature suddenly changes from a constant value \( T_c \) to a varying value with gradient \( G_T \); and with uniform gradient and constant speed the probe experiences a temperature change at a constant rate. After the probe is raised up to a certain height, at the position \( c \), let the scan change direction. Then the reversed processes begin. The true temperature environment experienced by the thermocouple during this whole scan is shown in Figure 2.7 by a solid line, where the scan intervals II and III are in the gradient zone and the scan intervals I and IV are in the convective zone. It should be noted that the position \( b' \) is the same position as \( b \) and the position \( a' \) is the same position as \( a \) but at a different traveling time and a different direction of motion of the thermocouple.

The temperature environments in each region are:

\[
G(t) = \begin{cases} 
T_c & t_a \leq t \leq t_b & \text{I} \\
T_c - \gamma(t - t_b) & t_b \leq t \leq t_c & \text{II} \\
T_c - \gamma(t_c - t_b) + \gamma(t - t_c) & t_c \leq t \leq t_{b'} & \text{III} \\
T_c & t_{b'} \leq t \leq t_{a'} & \text{IV}
\end{cases} 
\]

(2.8)

where \( T_c \) is a constant temperature in the convective zone and \( t_a, t_b, t_c, t_{b'}, t_{a'} \).
Figure 2.7: The dynamic response of the thermocouple and its compensation. The solid line is the postulated temperature environment experienced by the thermocouple during the whole scan process where from \( a \) to \( b \) is in the convective zone and from \( b \) to \( c \) is in the gradient zone. At the position \( c \) the scan changes direction, and \( b', a' \) are the same positions as \( b \) and \( a \) but at a different traveling time of the thermocouple. The dashed line which is calculated from Equation 8 is the temperature profile for a sensor with a time constant \( \tau = 2.5 \) sec. The values from the dashed curve at equal time increments are used for the compensation calculations; see Equation 2.7. The compensated values calculated are shown as rectangular markers in this plot.
are the times at which the probe reaches the positions \( a, b, c, b', a' \) (\( a \) and \( a' \), \( b \) and \( b' \) are the same position in space). The parameter \( \gamma = G_T v_s \) is the time rate of change of the temperature experienced by the temperature probe as the probe moves vertically in the gradient zone. In this expression, \( G_T \) is the temperature gradient and \( v_s \) is the scan speed.

The solutions to Equation 2.2 that satisfy the above temperature environments and the continuity conditions between each region are:

\[
T(t) = \begin{cases} 
T_c & \text{I} \\
(T_c - \gamma(t - t_b)) + \gamma \tau (1 - e^{-(t-t_b)/\tau}) & \text{II} \\
(T_c - \gamma(t_c - t_b)) + \gamma(t - t_c) - \gamma \tau [1 - (2 - e^{-(t_c-t_b)/\tau})e^{-(t-t_b)/\tau})] & \text{III} \\
T_c - \gamma \tau (1 - e^{-(t_c-t_b)/\tau})e^{-(t-t_b)/\tau} & \text{IV}
\end{cases}
\]

Let the time constant of a temperature probe be 2.5 sec and the constant temperature in the convective zone be \( T_c = 40 \degree C \). A constant gradient \( G_T = 100 \degree C/m \) may be assumed in the gradient zone along with a scan speed of 12 cm/min, which makes the parameter \( \gamma = 0.2 \degree C/sec \). The dashed line in Figure 2.7 shows the temperature profile that would be measured by this temperature probe.

The curve shows very clearly that in this case the time response of the probe shifts the apparent temperature distribution by approximately one time constant and makes the sharp boundary softer in both interface regions, especially when the probe returns from the gradient zone back to the convective zone. These characteristics of the temperature scan curve are
exactly what we observed in our laboratory experiments and what are commonly seen in solar pond temperature scans in which the sharpness of the convective-gradient boundary appears different for the scan up from what it is for the scan down.

To illustrate the effectiveness of the compensation method described in Section 2.5.1, the temperature values from the dashed curve in Figure 2.7 evaluated at equal time increments are used for the compensation calculation. The compensated values calculated from the Equation 2.7 are shown in Figure 2.7 as rectangular markers. The agreement of the compensated values and the postulated true temperature environment gives us confidence to use this method in the data analysis to correct the experimental observations and to obtain the better interpretations of the experimental results.

A sample compensation for the boundary salinity scan in our laboratory experiment is shown in Figure 2.8, which gives an excellent demonstration of the usefulness of the compensation method. The dashed line is drawn through the measured data points and the markers are compensated values. In this plot the scan speed was 12 cm/min and the scan changed direction 20 sec after it started.

2.5.3 Temperature and Salinity Fluctuations

Another use of the time delay compensation method is for the measurements of the temperature and salinity fluctuations in the vicinity of the convective-gradient boundary. In these measurements, an oscillatory environment can
Figure 2.8: The compensation of the sensor's response for the salinity measurement data from the laboratory experiment. The dashed line is drawn through the measured data points (x) and the rectangular markers give the compensated curve. In this plot, each compensated value is made by using the average of adjacent readings from the measurement results and the difference between these two readings, Equation 2.7.
be considered. A typical plot of thermocouple response observed in our boundary studies is shown in Figure 2.9.

The fluctuations can be characterized by the frequency and the amplitude of the Fourier components into which they can be decomposed. To simplify the initial discussion, a sinusoidally varying temperature is assumed to obtain the general behavior of the time response of the probe in a varying temperature environment. The time response equation is

$$\frac{dT}{dt} = -1/\tau(T - X \sin \omega t) \quad (2.10)$$

where $X$ is the characteristic amplitude and $\omega$ is the characteristic frequency of the fluctuation.

The solution of the above equation is

$$T = Ce^{-t/\tau} + \frac{X}{\sqrt{1 + \omega^2 \tau^2}} \sin(\omega t + \Phi), \quad (2.11)$$

where $\Phi = \tan^{-1}(-\omega \tau)$. The first term of the solution represents a transient term, which dies out after a time equal to a few time constants. The remaining periodic term is the long time response.

It is clear that the measured amplitude of the fluctuation is less than the true value by a factor of $1/\sqrt{1 + \omega^2 \tau^2}$, and the peak values of the measured temperature fluctuation are shifted in time from the true peaks. Both of these errors strongly depend upon the fluctuation frequencies. Therefore, the effect of the sensor response time is to greatly reduce the amplitude of short period variations but not to affect so much the longer period variations observed in our boundary temperature and salinity fluctuation experiments.
Figure 2.9: Typical response of a fixed thermocouple to temperature fluctuations in the vicinity of the convective-gradient boundary. Readings were taken digitally at one second intervals with an instrument having experimental uncertainty of 0.005°C to 0.010°C in relative values.
The general method of the time delay compensation can be also used in such an oscillatory environment. In the compensation calculations, the decomposition of the fluctuation into components is not necessary. The raw data can be input into Equation 2.6 or Equation 2.7 directly to obtain the compensated values one after another.

Figure 2.10 shows the results of a typical compensation calculation, made using a 2.5 sec time constant as measured for our probe. It will be noted that the corrected curve shown as a solid line is characterized by small short period oscillations, the period of which is derived from the one second time spacing of the observations. It seems clear that these oscillations arise from instrumental fluctuations in individual observations and do not represent real temperature behavior. When the thermocouple was placed in a constant temperature environment the output signal fluctuated by from 0.20 °C to a maximum of 0.40 °C, corresponding to a temperature uncertainty from 0.005 °C to 0.010 °C. Differences of this magnitude between successive thermocouple readings correspond quantitatively to the amplitudes of the short period peaks that appear in the corrected curve. If we introduce some smoothing of the data, one of the simplest procedures being to replace the data points by the means (appropriately time shifted) of each pair of adjacent data points, we obtain the smoother and probably more realistic corrected curve shown compared with the observed curve in Figure 2.11. A three point running mean in which each point is averaged with the mean of the points preceding and following gives very nearly the same result for our data. (Such a running
Figure 2.10: Compensation of thermocouple response for time constant. The dashed curve is the sensor response, a portion of the same data as plotted in Figure 3, and the solid curve is the estimate of actual temperature variations calculated from Equation 6b. As noted in the text, the oscillations of two second period conspicuous for example between 30 sec and 60 sec can be accounted for by uncertainty in the experimental data and do not represent real temperature oscillations.
Figure 2.11: Compensation of smoothed thermocouple response for time constant. The dashed curve is the sensor response, the same data as in Figure 4. Before calculating the corrected curve using Equation 66 the data were smoothed by replacing all data points by the time-shifted means of all pairs of adjacent data points.
mean is equivalent to taking the mean values of adjacent two-point means
and it thus represents more smoothing than the procedure we adopted.)

As expected from the behavior of a single frequency component described
by Equation 2.11, the corrected curve is larger in amplitude and shifted to
earlier time than the sensor response.

2.5.4 Determination of Time Constant

In order to make the computation to correct the data for sensor time constant,
we must know the time constant.

As shown in Section 2.5.1, the time constant of the temperature probe
is \( \tau = MC/Ah_e \), where \( h_e \) is the effective surface heat-transfer coefficient
which strongly depends on the condition of fluid flow around the probe.
In our experiments, two types of measurement procedure were used. In
the temperature and salinity scans, the measurements were made as the
probes moved through the fluid. In the temperature and salinity fluctuation
measurements, the probes were fixed at a certain position. It is clear that
the effective surface heat-transfer coefficients and thus the time constants
may differ for these two different measurement procedures. Therefore it
can be assumed that the time constant of the probe must be determined
independently for each different measurement procedure in the fluid.

A method which is used to determine the time constant \( \tau_m \) when the
probe is moving, and the time constant \( \tau_f \) when the probe is fixed, in the
solar pond temperature and conductivity measurements involves making a
short range scan entirely within the gradient zone. The procedure used is as follows.

The first step of this procedure is to chose a region within the gradient zone in which the scan will be made. This region should be far away from the convective-gradient boundaries to avoid environmental fluctuations, and the temperature and salinity distribution in this region should be as linear as possible. The probe is placed at the position $a$ in this region initially and allowed to approach equilibrium. The measurements are started with the probe fixed at this position for a period of time, $20\text{sec}$ for instance, and then the probe scans downward a certain distance.

The scanning distance should be long enough, such that the scanning time is much greater than $3\tau_m$, for the probe response to approach a straight line if the measurement environment is a constant gradient. For the temperature and salinity probes used in our experiments, $\tau_m \approx 2.5\text{sec}$, and the traveling distance has been chosen as $4\text{cm}$ which corresponds to a $20\text{sec}$ traveling time for the scan speed of $12\text{ cm/min}$.

After the down scan is finished at the position $b$, measurements are taken continuously until the probe approaches a new equilibrium, another $20\text{sec}$ for example. Then the same measurement procedure is repeated but the probe scans upward at this time. The complete measurement results in time sequences from this scan procedure are shown in Figure 2.12 (a). In this figure, the solid line is the measurement environment curves $G(t)$, which are constants during the time the probe is stationary and straight lines during
the time the probe is moving. The dashed line is the probe response. The state of the probe during each period of time is marked as stationary, up scan or down scan on the graph and the positions of the probe are marked as \(a\) and \(b\) at the time scans begin or end.

From the previous discussion, Section 2.5.2, at a long traveling time after the probe moving starts (say, \(t > 3\tau_m\)), the measured curve \(T(t)\) is approximately parallel to the true measurement environment \(G(t)\) and a given value of \(T(t)\) corresponds to the \(G(t)\) at a time \(\tau_m\) earlier, as follows from Equation 2.9(II). Thus the moving time constant \(\tau_m\) is simply the time spacing between the \(G(t)\) and \(T(t)\) curves after \(e^{-t/\tau_m}\) has decayed to a small value. In particular, if the up and down scans are plotted time shifted relative to each other so that they begin and end at the same points on the time scale, as in Figure 2.12 (b), then the \(G(t)\) curves (which are postulated to be straight lines) cross at the midtime point and the \(T(t)\) curves cross at a time \(\tau_m\) later than midtime. Thus the time constant \(\tau_m\) can be determined geometrically by observing the time difference between these two crossing points.

The exponential decay curves after the probe stops in Figure 2.12 can be used to determine the time constant \(\tau_f\) when the probe is fixed. If we take the measured values \(A_0, A'\) and \(A_\infty\) at three particular times called \(t_0, t'\) and \(t_\infty\), where \(t_0\) is the time at which the scan just stops, \(t_\infty\) is the time at which the probe achieves equilibrium and \(t'\) is the time at which the value of \((A' - A_\infty)\) is 0.386\((A_0 - A_\infty)\), the time constant \(\tau_f\) is just \((t' - t_0)\). This is
Figure 2.12: Determination of the sensor's time constants. The sensor is placed in the gradient zone and achieves equilibrium. Then it scans downward for a certain distance and stops at b. After a period of time, the scan reverses. The measurements are made before, during and after the scan. In plot (a), the solid curve is the postulated constant gradient from a to b and the dotted curve is the curve which is calculated by Equation 8 for a sensor with a time constant of 2.5 sec. The results are plotted in time sequence. In plot (b), up scan is plotted with time shifted so that it begins and ends at same points on the time scale as the down scan. The time difference between the two crossing points in this plot is the moving time constant $\tau_m$. The stationary time constant $\tau_f$ can be determined by using Equation 11 where the values of $A_0$, $A'$, and $A_\infty$ can be obtained from the plot at three particular times $t_0$, $t'$ and $t_\infty$. 
the result of the exponential decay equation which is

\[ \tau_f = (\ln \frac{A_0 - A_\infty}{A' - A_\infty})(t' - t_0). \]  

(2.12)

This expression holds for any \( t' \) and \( A' \) in the region of exponential decay. Thus any \( t' \) and \( A' \) can be used to determine the time constant \( \tau_f \) in general.

This geometrical method for the determination of both \( \tau_m \) and \( \tau_f \) was applied to determine the time constants of the temperature and conductivity measurement probes in our laboratory measurement system. The plot we obtained was very similar to Figure 2.12. Because the scan speed is relatively slow, the difference between \( \tau_m \) and \( \tau_f \) is not significant in our case. The determined values for both the temperature probe (thermocouple) and the conductivity probe are approximately 2.5 sec.

2.5.5 Discussion

We saw earlier in comparing Figure 2.10 and Figure 2.11 that this method of correcting for probe time constant is usable only if the function derived from the original data is sufficiently smooth. This requirement is fairly stringent, because the correction depends upon the time rate of change, and the experimental error in finding the time rate of change from observed data is necessarily much larger than the error in finding the quantity itself at any given time. (Proportional error in rate of change is larger because it involves the difference between adjacent nearly equal quantities.)

It must be realized also that this compensation procedure is useful only when the sensor time constant \( \tau \) is of the same order as or smaller than the
characteristic time of the quantity to be measured, and when there are at least several data points within the shortest characteristic time so that the estimated rate of change has some meaning. The requirement that the time constant \( r \) be not too large is evident in the correction formula, Equation 2.6, in which the size of the correction to be made is directly proportional to \( r \).

With these conditions met we have found that the correction procedure described here is useful in providing a more accurate description of the temperature and salinity phenomena studied. Profile distortions and non-physical asymmetries are nearly eliminated, as shown in Figure 2.8, and the amplitude and phase of fluctuating phenomena are better represented than in the uncorrected data.
References


CHAPTER III

Prediction and Observation of Internal Instability in Gradient Zone

3.1 Introduction

3.1.1 Static Stability and Oscillatory Instability

As discussed in Section 1.2, a solar pond cannot operate without an internally stable gradient zone in which both temperature and salinity increase downward and the gradients are negative as a function of height. In this gradient configuration, the hotter fluid on the bottom inherently stores potential energy that can be released if the system is disturbed. With the salt concentration on the bottom higher than at the top, it compensates for the effect of thermal expansion in decreasing the density and makes the system stable.

The individual contributions of temperature gradient $\partial T/\partial z$ and salinity gradient $\partial S/\partial z$ to the net density gradient $dD/dz$ can be expressed as

$$\frac{1}{D} \frac{dD}{dz} = -\alpha \frac{\partial T}{\partial z} + \beta \frac{\partial S}{\partial z},$$

(3.1)
where \( \alpha \) and \( \beta \), the coefficients of expansion due to each component, are

\[
\alpha = -\frac{1}{D} \left( \frac{\partial D}{\partial T} \right)_S,
\]

\[
\beta = \frac{1}{D} \left( \frac{\partial D}{\partial S} \right)_T.
\]

To prevent gravitational overturn, the net local density distribution must either be uniform or increase downward to meet the minimum buoyancy requirement for static stability. Therefore, the balance of the stabilizing and unstabilizing effects gives the criterion for marginal static stability which can be written as

\[
\beta \frac{\partial S}{\partial z} - \alpha \frac{\partial T}{\partial z} = 0.
\]  \hspace{1cm} (3.2)

If we define \( G_S \equiv \frac{\partial S}{\partial z} \) and \( G_T \equiv \frac{\partial T}{\partial z} \), the static stability criterion of Equation 3.2 can be expressed in short as

\[
G_S = \frac{\alpha}{\beta} G_T.
\]  \hspace{1cm} (3.3)

However, this static marginal stability criterion is not quite adequate to insure dynamic stability. Once the fluid is set in motion by any small external disturbance, convection can be sustained from the energy stored in the temperature gradient.

The oscillatory nature of the growth of dynamical instability has been explained in elementary terms by Nielsen [1]. In his discussion a fluid with salinity and temperature gradients such that the density is uniform is considered, while salinity and temperature are both increasing downward. Let a small element of fluid be displaced upward a distance \( \delta z \) during a short time...
interval $\delta t$ and then released. As it moves away from its equilibrium position, it will exchange its temperature and salinity with the surrounding fluid. Since the temperature diffusivity is approximately 100 times greater than the salinity diffusivity, the upward displaced fluid element will change very little in salt content during the displacement, but it will lose appreciable heat to the surrounding fluid. In consequence it will become denser than it was, and in falling down it will gain more energy than was used in displacing it upward. When the fluid element reaches its initial position, it will overshoot, then will gain heat and rise up again. The same process will be repeated and the net result is that a small disturbance to the system will create a growing oscillation in amplitude, resulting eventually in mixing. This phenomenon is often called overstability.

3.1.2 Dynamic Stability Criterion

Because of the oscillatory instability, the marginal static stability criterion of Equation 3.3 is not sufficient to prevent occurrence of oscillations and the stability criterion must be increased to a dynamic value. As a special example of a double-diffusive system with a very thick gradient zone and high saline Rayleigh number $R_S$, the results from the double-diffusive stability analysis have been often applied to the internal processes in solar ponds [2] [3].

Studies of the dynamic stability criterion of a fluid layer with uniform salt and temperature gradients were first carried out by Stern [4] and Veronis [5]
In their studies, the upper and lower boundaries were assumed to be dynamically free and thermodynamically free. The stability of the fluid layer is characterized by a destabilizing thermal Rayleigh number and a stabilizing saline Rayleigh number. The Rayleigh numbers are

\[
R_T = \frac{gaG_Td^4}{v\kappa_T},
\]

\[
R_S = \frac{g\beta G_Sd^4}{v\kappa_T},
\]

where \( g \) is the gravitational acceleration, \( \alpha \) and \( \beta \) are the density expansion coefficients with respect to temperature and salinity as defined above, \( G_T \) and \( G_S \) are the temperature and salinity gradients across the layer with the thickness \( d \), \( v \) is the kinematic viscosity, and \( \kappa_T \) is the thermal diffusivity of the fluid. For a fixed saline Rayleigh number \( R_S \) across a vertical extent of the fluid, it was determined that the instability to infinitesimal perturbations will first occur as overstable oscillations at a critical value of the nondimensional temperature difference, the thermal Rayleigh number \( R_T \).

Baines and Gill [7] performed an analysis of this problem for positive and negative thermal and saline Rayleigh numbers. They found that the layer became unstable to small perturbation when

\[
R_T = \frac{\nu/\kappa_T + \kappa_S/\kappa_T}{\nu/\kappa_T + 1} R_S + (1 + \kappa_S/\kappa_T)(1 + \kappa_s/\nu)\frac{27\pi^4}{4}
\]

where \( \kappa_S \) is the salinity diffusivity. This stability criterion is indicated by the solid line in Figure 3.1 for \( \nu/\kappa_T = 4.6 \) and \( \kappa_S/\kappa_T = 1/80 \) which are the typical values found in solar pond. For certain \( R_S \), if \( R_T \) is over the stability boundary, the system will be unstable.
Figure 3.1: Dynamic stability diagram of gradient zone for \( Pr = \frac{\nu}{\kappa_T} = 4.6 \) and \( Le = \frac{\kappa_T}{\kappa_S} = 80 \) which are the typical values found in solar pond. In this diagram \( R_S \) is the saline Rayleigh number, \( R_T \) is the thermal Rayleigh number. (From Ref. 1).
Because the typical values of saline Rayleigh numbers in solar ponds range from $10^{12}$ to $10^{14}$, the second term on the right side of the Equation 3.4 is much smaller than the first term. Thus, the second term can be neglected and the above stability criterion can be simplified as

$$R_T = \frac{\nu/\kappa_T + \kappa_S/\kappa_T}{\nu/\kappa_T + 1}$$

which was originally suggested by Weinberger [8] as the stability criterion for solar ponds.

The stability criterion also can be written as the relation between temperature gradient and salinity gradient, that is

$$G_s = \left(\frac{\nu + \kappa_T}{\nu + \kappa_S}\right)\frac{\alpha}{\beta}G_T.$$  \hspace{1cm} (3.6)

In this expression, $G_T$ is the temperature gradient within the gradient zone of the solar pond, $G_s$ is the required minimum salinity gradient for dynamic stability within the same region. The term $[(\nu + \kappa_T)/(\nu + \kappa_S)](\alpha/\beta)$ is called the stability coefficient which is sensitive to both temperature and salinity, hence varies with vertical position $z$ within the gradient zone. Since $(\nu + \kappa_T)/(\nu + \kappa_S)$ is always larger than 1, the salinity gradient required to satisfy the dynamic stability criterion is always greater than that required by the static stability criterion, which is Equation 3.3, for the same temperature gradient.

The above stability criterion was derived based on the assumption of linear temperature and salinity distributions. However, in a solar pond neither
the temperature gradient and the salinity gradient nor the physical properties of the fluid are likely to be constants. Zangrando [9] studied the stability of the gradient zone under variable gradient conditions in an experimental solar pond. In these experiments, instability resulted in the formation of one or more internal convective zones located about the weakest points in the salinity gradient. The thickness of these internal convective zones ranged from 3 to 10 cm.

Walton [10] analyzed the condition of a constant temperature gradient with a variable salt gradient for large thermal and saline Rayleigh numbers. The analysis showed that when convection occurs, it takes the form of an overstable mode and the Equation 3.4 can be used to estimate instability anywhere in the gradient zone, as long as the Rayleigh numbers are calculated from the local value of the gradient. Walton's analysis agrees with the experimental results of Zangrando within the accuracy of the measurements. Zangrando and Bertram [11] studied the same problem in a series of numerical calculations. The numerical results approach Walton's asymptotic solutions at large $R_s$, but differ significantly at smaller $R_s(< 10^8)$. Their work indicates that an instability will be produced at an inflection point on the salinity profile where the salinity gradient has a minimum value. Non-uniform salinity gradients have also been studied by Kaviany and Vogel [12].
3.1.3 Local Dynamic Stability

As discussed in Section 3.1.2, for a constant temperature gradient and a nonlinear salinity profile, the instability is produced locally and located at the weakest salinity gradient. As one would intuitively expect, the behavior of the fluid layer in the gradient zone is governed by local gradient, not the gradient averaged over the whole region.

The layer thickness dependence of the dynamic instability is discussed by Nielsen [13]. It is noted that the second term in Equation 3.4 reveals the information about the relation between the layer thickness and the salinity gradient required by the stability criterion for a given temperature gradient. To illustrate this relation, a numerical calculation is performed. If $G_T = 0.4^{\circ}C/cm$ and the values of the various physical properties of the solution appropriate to a gradient region at 15% NaCl concentration and at 60$^{\circ}C$, the relation of the required salinity gradient and the layer thickness can be obtained as

$$2.061 \times 10^4 d^4 = 4.673 \times 10^7 G_s d^4 + 674.$$ 

In this relation, c.g.s units ($G_s$ in $gm/cm^4$, $d$ in cm) are used. The results of evaluation of $G_s$ for various values of $d$ are shown in Table 3.1.

From Table 3.1, it is seen that there is very little change in the $G_s$ for marginal stability down nearly to 1cm, and that at 0.425cm the system is marginally stable entirely without any solute gradient. This limiting case is simply the purely thermal case. Nielsen pointed out that in the second term of Equation 3.4, the value $27\pi^4/4$ is calculated for particular mechanical
Table 3.1: Evaluation of $G_S$ and $R_T$ for various values of $d$. (From C. E. Nielsen [13]). In this table, $G_S$ is in $gm/cm^4$.

<table>
<thead>
<tr>
<th>$d$</th>
<th>$\infty$</th>
<th>$10\text{cm}$</th>
<th>$1\text{cm}$</th>
<th>$0.5\text{cm}$</th>
<th>$0.425\text{cm}$</th>
</tr>
</thead>
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<td>$G_S$</td>
<td>$4.41 \times 10^{-4}$</td>
<td>$4.41 \times 10^{-4}$</td>
<td>$4.27 \times 10^{-4}$</td>
<td>$2.10 \times 10^{-4}$</td>
<td>$0.00 \times 10^{-4}$</td>
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<tr>
<td>$R_T$</td>
<td>$\infty$</td>
<td>$2.06 \times 10^8$</td>
<td>$2.06 \times 10^4$</td>
<td>$0.129 \times 10^4$</td>
<td>$672$</td>
</tr>
</tbody>
</table>

and thermal boundary conditions that certainly do not correspond exactly to pond boundary conditions; however even if this value is wrong by a factor of three either way [14] one can still conclude that layers of the order of 0.4$cm$ or less would be stable with zero salinity gradient because of the $d^4$ dependence.

This result is important because it shows a layer a few centimeters thick, corresponding to $R_T \sim 10^6$, is just as stable or just as unstable as any arbitrarily thicker layer, for given values of the gradients. Therefore the instability threshold for any sublayer of at least a few centimeters thickness can be calculated from the marginal stability relation, Equation 3.6, using the local values of the gradients and other parameters.

This conclusion presents a practical method for the stability evaluation in solar ponds in which neither temperature gradient nor salinity gradient are uniform. Since only local properties and local gradients are relevant to the dynamic stability condition, in order to calculate the pre-existing stability it is appropriate that Equation 3.6 should be applied to successive layers.
of small finite thickness. The absolute stability of relative positions within
the vertical gradient can then be established by undertaking evaluation of
Equation 3.6 at incremental depths.

3.1.4 Objectives of Investigation

In order to understand the dynamical processes of the internal instability,
Nielsen [1], Zangrando [9], Swift [15] and some others [16] [17] have investig­
gated the gradient breakdown in operating solar ponds. Almanza and Bryant
[18] have observed oscillation on temperature in the gradient zone. In a lab­
oratory experiment, Kirkpatrick, Gordon and Johnson [19] have studied the
stability of a fluid layer with nonuniform temperature and salinity gradient
and found that fluid instability was initially oscillatory, occurred at the point
of minimum salinity gradient and resulted in the formation of a thin mixed
layer. However, the oscillatory nature of the internal instability within the
gradient zone with nonlinear temperature and salinity profile still have not
been as extensively studied experimentally as the linear case especially in the
comparison of the experimental observations with the theoretical results.

In the previous theoretical dynamic stability analysis, the thickness in­
volved in the stability criterion was considered as overall thickness of the
double diffusive layer. To predict fluid instability, a length scale must be
chosen so the stability criterion and experimental stability parameter can be
compared. This procedure is not convenient for practical uses because of the
difficulty of finding a suitable length scale in the nonuniform gradients.
The objective of the investigations in this chapter has two parts: (1) to develop a practical method for the internal instability prediction of the gradient zone and to examine its usefulness in the tank experiment, (2) to investigate the oscillatory nature of the onset instability and compare with the theoretical calculations.

As a tool for the stability analysis, a local stability margin number and a practical stability analysis procedure are introduced, and the formulas for calculating the stability coefficient as a function of temperature and salinity are also established.

In order to investigate the generation processes of the internal convection within the gradient zone, two experiment runs were conducted in the experimental tank apparatus described in Chapter II. The processes were monitored by the temperature and salinity measurements and the local stability margin calculation developed in this chapter was used for predicting the onset of instability. The gradient breakdown was observed in both experiment runs and the temperature variation before the instability occurred was obtained in Experiment Run # 2. The oscillation frequency of the temperature variation was then determined by Fourier transform and compared with the theoretical calculations.
3.2 Dynamic Stability Margin Calculations

3.2.1 Evaluating of the Stability Coefficient

For a given pond temperature gradient, if the stability coefficient is known, the theoretical value of required salt gradient can be determined from Equation 3.6 directly. Thus, in practice, the calculation of a stability coefficient at various vertical positions within the salt gradient region becomes the basis of a stability evaluation.

Detailed information on the values of all the variables needed for evaluating Equation 3.6 exist, in various tables of brine physical properties [20][21]. A formula for calculating the stability coefficient has been established making use of a least-square curve fitting routine in which the Gauss-Jordan elimination method is used for finding the solution of the coefficient matrix.

The following formula gives the conversion from temperature and salinity into density,

\[ D(S, T) = \sum_{i=0}^{3} \sum_{j=0}^{3} A_{i,j} S^i T^j, \]  

(3.7)

where the values of \( A_{i,j} \) are given in Table 3.2 with \( T(\degree C) \) from 10 \( \degree C \) to 100 \( \degree C \), \( S(\%) \) from 0\% to 26\% and \( D \) in \( (kg/m^3) \).

The data are obtained from Kaufmann [21], given to 6 digits. The calculation error in determining \( D(S, T) \) is less than 0.03\%. It is recognized that the measurement of specific gravity of pond brine samples is the commonly adopted procedure by which salt concentration is assessed. The relationship between \( S.G.(20\degree C/20\degree C) \) and \% salt by weight is shown in Appendix C.
Table 3.2: The values of $A_{ij}$ for calculating $D(S,T)$.

<table>
<thead>
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<th>1</th>
<th>2</th>
<th>3</th>
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</thead>
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<td>7.3624 $10^{-4}$</td>
<td>4.7088 $10^{-4}$</td>
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<tr>
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<td>7.79520 $10^{-4}$</td>
<td>-9.3073 $10^{-6}$</td>
</tr>
<tr>
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<td>-5.9952 $10^{-3}$</td>
<td>3.7422 $10^{-4}$</td>
<td>-1.0436 $10^{-5}$</td>
<td>1.4816 $10^{-7}$</td>
</tr>
<tr>
<td>3</td>
<td>1.5332 $10^{-5}$</td>
<td>-9.3860 $10^{-7}$</td>
<td>3.2836 $10^{-9}$</td>
<td>4.0083 $10^{-10}$</td>
</tr>
</tbody>
</table>

The formula for the density (Equation 3.7) can be used in conjunction with the definition of $\alpha$ and $\beta$ to determine their values at the same temperature and salinity. The formulas for calculating $\alpha$ and $\beta$ are as follows:

$$\alpha = -\frac{1}{D} \left( \frac{\partial D}{\partial T} \right)_S = -\frac{\sum_{j=0}^{q} \sum_{i=0}^{q} j A_{i,j} S^{i-j}}{\sum_{j=0}^{q} \sum_{i=0}^{q} A_{i,j} S^{i-j}},$$  \hspace{1cm} (3.8)

and

$$\beta = \frac{1}{D} \left( \frac{\partial D}{\partial S} \right)_T = \frac{\sum_{i=0}^{q} \sum_{j=0}^{q} i A_{i,j} S^{i-1-j}}{\sum_{i=0}^{q} \sum_{j=0}^{q} A_{i,j} S^{i-j}},$$ \hspace{1cm} (3.9)

where $A_{i,j}$ are the same as in Equation 3.7. The formula for calculating $(\nu + \kappa_T)/(\nu + \kappa_S)$ can be written as

$$\frac{\nu + \kappa_T}{\nu + \kappa_S} = \sum_{i=0}^{2} \sum_{j=0}^{2} B_{i,j} S^{i-j},$$ \hspace{1cm} (3.10)

where the values of $B_{i,j}$ are given in Table 3.3.

By combining Equations 3.8 through 3.10, the stability coefficient can be determined anywhere within the gradient zone for given temperature and salinity distributions. The range of stability coefficient values (in % / °C)
Table 3.3: The values of $B_{i,j}$ for calculating $(\nu + \kappa_T)/(\nu + \kappa_S)$.

<table>
<thead>
<tr>
<th>$j \setminus i$</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.085</td>
<td>-1.532 $10^{-3}$</td>
<td>1.168 $10^{-5}$</td>
</tr>
<tr>
<td>1</td>
<td>2.550 $10^{-3}$</td>
<td>-3.902 $10^{-7}$</td>
<td>-1.935 $10^{-8}$</td>
</tr>
<tr>
<td>2</td>
<td>2.784 $10^{-5}$</td>
<td>-8.203 $10^{-7}$</td>
<td>2.757 $10^{-8}$</td>
</tr>
</tbody>
</table>

for the temperature range between 4 °C to 100 °C and salinity from 0 % to 25 % is from 0.4 to 16.1.

3.2.2 Introduction of a Stability Margin Number

Based on the concept of local stability, a stability margin number and a systematic procedure for the stability evaluation can be introduced [22]. The formulas developed in Section 3.2.1 are used as the tools for stability coefficient calculations.

The stability margin number is defined as $(G_S)_a/(G_S)$, where $(G_S)_a$ is the actual (measured) local salinity gradient (in %/m, for convenience), and $G_S$ is the indicated value (same units) required to satisfy the dynamic stability criterion for the given (measured) local temperature profile at height $z$ (in meters) within the pond gradient zone.

In principle, the localized margin number must be larger than 1 in order to sustain local stability; otherwise an instability may be expected to form in that layer. The margin number can be used to predict a localized safety
factor. In actuality, from solar pond practice, it is found that sometimes even if the calculated stability margin number slightly exceeds the value 1 in a layer, gradient breakdown can occur.

By checking localized margin numbers, the most unstable region within a salinity gradient can be readily determined. The general procedure for determining the margin of safety involves the following steps.

First, measure temperature and salinity profiles accurately and chart $T$ and $S$ values. In our expressions, the units for $T$ and $S$ are $^\circ C$ and % salt by weight respectively. This is simply a matter of convenience for our purposes. See Appendix C for conversion of $S$ values from S.G.(20°C/20°C) to % salt by weight.

Second, divide the temperature and salinity profiles into incremental intervals, and calculate actual temperature and salinity gradients. A 2cm to 5cm interval is the usual practice adopted in the stability analysis of laboratory tank experiments. Within that interval, temperature and salinity profiles can for expedience be treated as practically linear. Thus, $(G_S)_a$ and $(G_T)_a$ become $(\Delta S_a/\Delta z)_j$ and $(\Delta T_a/\Delta z)_j$ respectively.

The third step is to calculate $T_j$ and $S_j$, needed in order to evaluate the safety coefficient of layer $j$. The average temperature $\overline{T_j}$ and average salinity $\overline{S_j}$ in the $j$ the layer can be obtained by averaging maximum and minimum values of temperature and salinity in the layer. Insert $\overline{T_j}$ and $\overline{S_j}$ into Equation 3.10, and in addition evaluate $\alpha$ and $\beta$ using Equation 3.8 and Equation 3.9. In this way a local safety coefficient is determined.
Finally, determine a local stability margin number. Using the local safety coefficient and local temperature gradient, the internal gradient required to satisfy the dynamic stability criterion can be calculated from Equation 3.6. In this case, $G_s$ should be written as $\Delta S/\Delta z$. The ratio of $(\Delta S_s/\Delta z)_j$ and $(\Delta S/\Delta z)_j$ is the local dynamic stability margin number which predicts the relative safety of gradient layer $j$. This calculation should be repeated for successive layers within the gradient zone.

The usefulness of the described local stability analysis procedure is checked by applying it to the FSR solar pond at The Ohio State University, Columbus, Ohio, in which instability has been observed to have occurred.

This pond was built by Nielsen in 1975, is nearly 350m in surface area and has a maximum 2.5 m depth [23]. It is still in operation. NaCl salt is used in the pond. The maximum temperature which has been reached is about 62°C. The gradient of the pond was observed to have broken down on June 27, 1980. The temperature and salinity profiles before and after the breakdown are shown in Figure 3.2. Recorded temperature (chart record) data shows that the instability began at around 30cm below the upper boundary and eventually propagated to become a succession of layers encompassing a width of about 55cm in the gradient region (see Figure 3.2).

The temperature and salinity data recorded during the 5 days prior to the breakdown are used to calculate the stability margin profile. The calculation result, see Figure 3.3, indicates that the most unstable region is between a depth of 25cm to 30cm (relative to zone boundary = zero depth) with the
Figure 3.2: Temperature (°C) and Salinity (%) profile data, recorded for the 350m Farm Science Review pond at The Ohio State University, during mid-1980. The dashed lines (1) indicate the smooth temperature and salinity profiles recorded prior to a breakdown event. The solid lines (2) and (3) show chart recorded temperature scans made soon after breakdown commenced (2) and sometime later (3). Solid and open circles on the salinity graphs indicate actual sample measurements of salinity.
Figure 3.3: The dimensionless stability margin number (simply called safety number in this figure), as a function of pond depth (cm), for FSR pond.
minimum margin number about 1.35.

A similar procedure was also applied to two other solar ponds at different locations for stability calculation [15] [16]. Given the uncertainty of experimental data, general agreement on the gradient instability appearance and the breakdown location has been found between observation of instability and stability margin calculation. The results have shown that the predicted instabilities agree satisfactorily with the observations. This agreement indicates the reliability of the method used to evaluate the gradient stability. Thus, this stability analysis procedure is used throughout our laboratory experiments to predict the local dynamic stability and to assist in understanding the dynamic processes occurring.

3.3 Observations of Gradient Breakdown in the Present Experiments

3.3.1 Experimental Procedures

The experimental procedures to investigate the processes of internal gradient breakdown and the oscillatory nature of the instability in the gradient zone are described in detail in this section.

In order to approach a weak enough salinity gradient so that the occurrence of the instability may be expected, a fast injection method was used to modify the salinity distribution and to make a weak gradient region in the gradient zone. During the salinity profile modification, brine was injected
into the gradient zone through a diffuser with a 0.5\textit{mm} gap and mixed with the environment solution. The diffuser was placed at the top of gradient zone and scanned stepwise downward. The injection rate was well controlled and the scanning procedure was repeated until the desired salinity distribution obtained. Detailed description of the salinity modification is given in Appendix B. After injection, 30 hours were waited for the gradient smoothing up, then the salinity samples were taken and weighed to obtain the salinity profile as the initial salinity condition.

The time-dependent behavior of the salt distribution which provide qualitative information on the response of non-constant gradient zone to the change in salinity has been examined by several researchers [1] [24] [25]. In their results, a salinity time constant can be defined as

\[ t_{\text{salt}} = \frac{d^2}{\kappa_S} \]

where \(\kappa_S\) is the solute diffusivity coefficient, and \(d\) is a characteristic length. Assume the half thickness of the weak gradient region is \(d = 5\text{cm}\) and \(\kappa_S = 3 \times 10^{-5}\text{cm}^2/\text{s}\); then the time constant \(t_{\text{salt}} = 8.3 \times 10^5\text{s}\). Thus, it takes approximately 10 days for a change in salinity at the edge of the weak region to affect the salinity profile near the center 2\text{cm}. Since the total experiment duration for each run was less than 2 days, it is assumed that nondiffusional hydrodynamics dominated the development of the salinity profile before the gradient break down. Therefore, the initial salinity sampling was used for the instability prediction at every stage during the experiment until convection occurred.
The increasing temperature gradient with time was obtained by heating from the bottom. The heating rate at the first run is 150W and at the second run is 170W. Since the lower convective zone is very thick, about 70cm, the temperature increase in the lower convective zone is very slow, less than 0.36°C/hr typically. The average changing of temperature gradient in the gradient zone is estimated to be 0.008°C/cm.hr. Compared with the average temperature gradient of 0.7°C/cm, it is one percent gradient change during one hour. This temperature gradient change was so slow that a quasi-equilibrium state of temperature distribution can be assumed.

During the experiments, the following quantities were measured. (1) The temperature distributions and the salinity distributions at the time interval of 0.5 hours were measured using the scan of thermocouple and conductivity probes. Temperature and conductivity scans were along the vertical line of the center of the tank. All the temperature and salinity data were plotted to notify the occurrence of instability and to call the special attention during that period. (2) The salinity samples were taken before the heating started and just after the internal convective zone generated. Those samples were weighed and the results were plotted as the salinity distribution for stability analysis calculations. (3) The temperature fluctuations at the level that instability first occurred were measured by thermocouples fixed close to that level. (4) Heating rate was monitored by a power meter, and a fixed heating rate was kept during the experimental runs. (5) The temperature differences between the plastic tank and the guard cylinder were measured and controlled.
to less than 0.5°C to ensure a one dimensional modeling.

3.3.2 General Observations

Using the experiment procedure described in Section 3.3.1, two experiment runs were conducted and the occurrence of the instability in the gradient zone was observed in both experiment runs with different temperature and salinity configurations. The measured time dependent temperature and salinity profiles during the experiments are shown in Figure 3.5 and 3.6 for Experiment Run # 1, and in Figure 3.8 and 3.9 for Experiment Run # 2. The time in hours in these figures is referred from the beginning of each experiment run.

In both experiment runs, the appearance of the internal convective zone occurred within the region in which the salinity gradient was the weakest. The observed internal convective zones were generated suddenly in approximately 1cm and developed rather rapidly in thickness during the first couple hours after the gradient breakdown. In the Experiment Run # 2, the increasing in amplitude of the temperature oscillation before the occurrence of instability was also observed. The observed experiment results from both experiment runs are summarized in Table 3.4.

3.3.3 Experiment Run # 1

The initial temperature profile within the gradient zone and the initial salinity profile in the same region are shown in Figure 3.4. The initial temperature profile is nearly a straight line with a little curvature near the bottom which
Figure 3.4: The initial temperature and salinity profiles in the Experiment Run # 1.
is the region close to the lower convective zone.

A continuously varied curvature of the salinity distribution was made by the fast injection salinity modifications. The weakest salinity gradient region was from 80 cm to 84 cm in which the average salinity gradient was nearly a constant value which is 7%/m.

The heating power was increased from 30 W to 150 W at the time $t = 0 hr$. As the temperature at the lower convective zone increased, the heat propagated into the gradient zone. The temperature as well as the temperature gradient in the gradient zone increased with time. A fairly smooth and continuous temperature profile as shown in Figure 3.5 was kept until the time 12 hr after the heating started.

At $t = 13 hr$ irregularity of the salinity gradient was detected by the conductivity scan at the position around $z = 82 cm$ and a isothermal sublayer with the thickness of approximately 1 cm was observed in the temperature scan made at the same time. The thickness of this isothermal sublayer developed rather rapidly during the first couple hours immediately after the gradient breakdown. At $t = 17 hr$, the isothermal sublayer grew to 5 cm in thickness and at $t = 21 hr$, it was 8 cm. The development of the isothermal sublayer is presented in Figure 3.5.

Salinity samples taken at $t = 14 hr$ and $t = 23 hr$, which are 1 hr and 9 hr respectively after the gradient breakdown, gave the profiles shown in Figure 3.6. The occurrence and the development of an isosaline layer in the salinity profiles is consistent with the isothermal layer in the temperature
Figure 3.5: Time dependent temperature profiles for Experiment Run # 1.
Figure 3.6: Salinity profiles taken before and after the gradient breakdown for Experiment Run # 1.
profiles. Both the isothermal layer and isosaline layer in the temperature and salinity profiles represent an internal convective zone which is the result of the gradient instability caused by the increasing of the temperature gradient at that region.

3.3.4 Experiment Run # 2

The Experiment Run # 2 was conducted at the same manner as the Experiment Run # 1 excepted that the initial temperature and salinity distributions were different. In the Experiment Run # 2, the emphasis was on the measurement of the temperature variation in the gradient zone before the gradient breakdown to investigate the oscillatory nature of the onset of the instability. Besides the regular temperature and conductivity scan at each half hour, a rank of thermocouples was placed in the weakest gradient region to measure the time series of temperature oscillations at each level.

The initial temperature and salinity profiles which are shown in Figure 3.7 were taken at the time $t = 0$ hr when the heating started. It can be seen from Figure 3.7 that the initial temperature gradient in the Experiment Run # 2 is less than that in the Experiment Run # 1 by a factor of 2 while the salinity gradient at the weakest gradient region is from approximately 7%/m in the Experiment Run #1 down to approximately 3.5%/m in the Experiment Run # 2. Hence, it was expected that the onset of the instability could occur faster in the Experiment Run # 2 if the heating rate was kept the same as previously.
Figure 3.7: The initial temperature and salinity profiles of the Experiment Run # 2.
The heating was started with a power of $170W$ at $t = 0hr$. After 6 hours, an isothermal layer appeared at around $83cm$ in height with a thickness of $1cm$, shown in Figure 3.8. Two hours later, the thickness of the isothermal layer grew to $4cm$ and grew continuously to $6cm$ after another 2 hours. The salinity samples taken before and after gradient breakdown are plotted in Figure 3.9. The thickness of the isosaline layer in the salinity profile due to the gradient instability is consistent with the thickness of the isothermal layer in the temperature profile and represents the thickness of the internal convective zone.

The temperature oscillation taken at the position of $z = 83cm$ before and during the onset of the gradient instability is shown in Figure 3.10. The total measurement time for both cases is $0.5hr$. In Figure 3.10 (a) the data was taken $1.5hr$ before the gradient breakdown. The temperature oscillation is approximately $0.025°C$ which is in the order of background noise. In Figure 3.10 (b) the data was taken $1hr$ before the gradient breakdown and the amplitude of the oscillation increased to approximately 5 times larger than half hours before and reached maximum value of $0.12°C$. Since the temperature gradient at this region is $60°C/m$, the maximum bulk fluid oscillation associated with the maximum temperature oscillation is $2mm$. Another half hour later, the gradient breakdown was observed by temperature and conductivity scan. The observed increasing of amplitude on the temperature oscillation gives evidence that the onset of instability in the gradient zone first begins as the fluid oscillatory motion.
Figure 3.8: Time dependent temperature profiles for Experiment Run # 2.
Figure 3.9: Salinity profiles taken before and after the gradient breakdown for Experiment Run # 2.
Figure 3.10: Temperature oscillation before the gradient breakdown in Experiment Run # 2. (a) 1.5hr before the gradient breakdown. The oscillation was in the instrument background noise level. (b) 1hr before the gradient breakdown. The amplitude of the oscillation was significant increased to the maximum of 0.12°C which was the signal of the onset of gradient instability.
A summary list of observations made is given in Table 3.4.

Table 3.4: Summary of significant observations from the tank experiments.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run #1</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Run #2</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

3.4 Stability Analysis of Gradient Zone

3.4.1 Prediction of Instability

The stability margin numbers introduced in Section 3.2 were calculated during the experiment runs for predicting the onset of the gradient instability and the breakdown location. To calculate the stability coefficient, the salin-
ity samples taken at the time each experiment run began were used as the salinity distribution and the temperature data were obtained from the temperature scans hourly. The space interval was chosen as 2 cm for local stability calculation and the average temperature and salinity values in this interval were used for calculating the local fluid properties. The stability margin calculations were done once an hour until the internal convective zone established. The calculation uncertainty was estimated to be ±0.4 on safety margin numbers.

The temperature and salinity data as well as the calculated stability margin number at the time just before the instability occurred are given in Table 3.5 and Table 3.6 for each experiment run.

Table 3.5: Temperature and salinity data and calculated safety margin number at half hour before gradient breakdown in Experiment Run # 1.

<table>
<thead>
<tr>
<th>Z (cm)</th>
<th>T (°C)</th>
<th>S (%)</th>
<th>G_T (°C/m)</th>
<th>G_S (%/m)</th>
<th>Safety #</th>
</tr>
</thead>
<tbody>
<tr>
<td>87.0</td>
<td>43.8</td>
<td>9.51</td>
<td>100</td>
<td>22.0</td>
<td>2.7</td>
</tr>
<tr>
<td>85.0</td>
<td>45.8</td>
<td>9.95</td>
<td>100</td>
<td>11.5</td>
<td>1.4</td>
</tr>
<tr>
<td>84.0</td>
<td>47.8</td>
<td>10.18</td>
<td>105.0</td>
<td>8.5</td>
<td>0.9</td>
</tr>
<tr>
<td>81.0</td>
<td>49.9</td>
<td>10.35</td>
<td>115.0</td>
<td>6.5</td>
<td>0.6</td>
</tr>
<tr>
<td>79.0</td>
<td>52.2</td>
<td>10.48</td>
<td>115.0</td>
<td>10.0</td>
<td>0.9</td>
</tr>
<tr>
<td>77.0</td>
<td>54.5</td>
<td>10.68</td>
<td>135.0</td>
<td>13.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Table 3.6: Temperature and salinity data and calculated safety margin number at half hour before gradient breakdown in Experiment Run # 2.

<table>
<thead>
<tr>
<th>Z(cm)</th>
<th>T(°C)</th>
<th>S(%)</th>
<th>G_T(°C/m)</th>
<th>G_S(%/m)</th>
<th>Safety#</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.0</td>
<td>34.0</td>
<td>8.37</td>
<td>55.0</td>
<td>69.0</td>
<td>17.9</td>
</tr>
<tr>
<td>87.0</td>
<td>35.1</td>
<td>9.75</td>
<td>50.0</td>
<td>19.0</td>
<td>5.3</td>
</tr>
<tr>
<td>85.0</td>
<td>35.1</td>
<td>10.13</td>
<td>50.0</td>
<td>7.5</td>
<td>2</td>
</tr>
<tr>
<td>83.0</td>
<td>37.1</td>
<td>10.28</td>
<td>60.6</td>
<td>3.5</td>
<td>0.8</td>
</tr>
<tr>
<td>81.0</td>
<td>38.3</td>
<td>10.35</td>
<td>65.0</td>
<td>6.0</td>
<td>1.2</td>
</tr>
<tr>
<td>79.0</td>
<td>39.6</td>
<td>10.47</td>
<td>95.0</td>
<td>10.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The stability margin numbers from Table 3.5 and 3.6 were plotted as the function of height in the gradient zone to predict the location of the instability. These plots are shown in Figure 3.11 and Figure 3.12 respectively.

In Experiment Run # 1, a minimum stability margin number of near 1 was calculated from the initial temperature and salinity profiles. However, there is no any evidence of the onset of the instability. Taking into consideration the measurement uncertainty, stability of the gradient at that time can be accounted for. By examining the safety margin plot at \( t = 12\, hr \), Figure 3.11, it was found that the safety number at 82cm dropped to 0.6. This number was well below 1, and indicated the onset of instability at this level. The prediction was confirmed by the temperature and conductivity profiles taken at the time of one hour later. (see Figure 3.5). At that time,
Figure 3.11: The stability margin number as a function of height calculated half hour before the gradient breakdown for Experiment Run # 1.
Figure 3.12: The stability margin number as a function of height calculated half hour before the gradient breakdown for Experiment Run # 2.
an isothermal layer of 1cm thick appeared at the level about 82cm.

Similar prediction was made successfully in the Experiment Run #2. In the safety number distribution plotted at \( t = 5hr \), the calculated stability margin number at \( z = 83cm \) was dropped from its initial value 1.7 to 0.8 in five hours. It was predicted that the instability would occur around that position. From the following temperature scan (see Figure 3.8), an isothermal layer of 1cm thick at 83cm was observed.

The predicted occurrence of the instability and the breakdown position in the gradient zone agree with the observations within the experiment error. This error is mainly due to the space measurement uncertainty of the sample taken and the error on the temperature gradient and salinity gradient measurements.

### 3.4.2 Frequency of Oscillatory Instability

As discussed in Section 3.1, the theoretical studies of the double diffusive convection have shown that the internal instability of the gradient zone first occurs as infinitesimal oscillations. In the case of overstability, Sani [26] has predicted that the amplitude of oscillations would be very small, while Veronis [5] has suggested that they would readily lead to a steady flow. For small \( \kappa_S/\kappa_T \) and large \( R_S \), the frequency of the neutral disturbances in the fluid layers with constant salinity and temperature gradient is given by

\[
f = \frac{1}{2\pi} \sqrt[3]{\frac{1}{3} (1 + \nu/\kappa_T)^{-1} g \beta G_S}. \tag{3.11}
\]

In this expression, \( f \) is the oscillation frequency in Hz, \( \nu/\kappa_T \) is the ratio
of the viscosity to thermal diffusivity, $g$ is gravitational acceleration, $\beta$ is salt expansion coefficient, and $G_S$ is the salinity gradient. In the consideration of local stability, the local salinity gradient value can be used. This oscillation frequency has been verified approximately by Wright and Loehrke [27] in a thin thermal saline layer and by Shirtcliffe [28] [29] in a sugar-water mixture experimentally.

In Experiment Run #2, an oscillatory effect of the onset of instability in the gradient zone has been observed as the temperature oscillation which is presumably the overstability predicted by the theories. The feature of this effect which can readily be checked against theory is the frequency of the oscillation.

The characteristic frequency of the measured temperature oscillation from Figure 3.10 (b) can be obtained by the means of Fourier transform. The intensity vs. frequency plot of the temperature oscillation is shown in Figure 3.13. The measured characteristic period of the temperature oscillation at the position about 83cm during the onset of instability is determined as 110sec.

The expected oscillation period can be calculated by inserting the local values of properties into Equation 3.12. At $T = 35^\circ C$ and $S = 10\%$, $\nu/\kappa T = 5.4$, $\beta = 6.8 \times 10^{-3}$ (in 1/%) for NaCl solution [30]. Taking $g = 980cm/sec^2$ and the minimum local salinity gradient as the half of the average value in that region, $G_S = 0.017%/m$. The calculated oscillation period is 81sec which is less than the observed characteristic period. Shirtcliffe also found
Figure 3.13: Frequency spectrum of the temperature oscillation at the onset of the instability. The characteristic period of the temperature oscillation determined from the highest peak in this spectrum is 110s.
that observed periods tended to be longer than the calculated periods.

3.5 Summary and Discussions

Using the concept of a localized stability margin and the result of linear stability analysis, a practically useful method for evaluating internal stability within the gradient zone with nonlinear temperature and salinity gradients is developed. The stability coefficient can be easily calculated by combining Equation 3.8 through Equation 3.10. The calculated density values represent the measured values [21] within a discrepancy of less than 0.03%. The discrepancy between the calculated stability coefficient and values in the table given by Zangrando [9] is less than 10%. The stability criterion is then applied to successive layers of small finite thickness and the local instability can be predicted.

The instability of the gradient zone was observed in both experiment runs in which both temperature gradient and salinity gradient were nonuniform. The fluid instability occurred at the minimum salinity gradient region and appeared as a convective layer a few centimeters in thickness initially. This phenomenon is the same as the observations from the operating solar ponds.

By checking the local stability margin number introduced in Section 3.2, the onset of instability can be predicted. The predicted occurrences and locations of instability agree with the experimental observations very well. This agreement further confirms the usefulness of the local stability margin calculation for the stability analysis in solar ponds.
The accuracy of the calculated stability margin number for predicting the onset of gradient instability is strongly depend on the accuracy of the salinity gradient measurement. The uncertainty of salinity gradient measurement is directly proportional to the uncertainty of space measurement which is ±0.2cm in our experiments. For the sample taken at each 2cm interval, the uncertainty on the determination of salinity gradient is at least 10%.

The onset of instability in the gradient zone does occur as the growth of very small amplitude oscillatory motions which is verified by the observations of temperature oscillations increasing in amplitude before the gradient breakdown. The maximum temperature oscillation observed was 0.12°C which corresponds to the maximum bulk fluid oscillation in the order of 2mm. The characteristic period of the oscillation is determined as 110sec and compared with the predicted value. The discrepancy between measurement and prediction is appreciable, and may be in part associated with the difference between the actual boundary conditions and those assumed in the theory.
References


CHAPTER IV

Structure of Temperature and Salinity Fluctuation at Gradient - Convective Boundary

4.1 Introduction

4.1.1 Balance of Transport Processes at Gradient - Convective Interfaces

The most important, most interesting and least well understood processes in solar ponds occur at the boundary between gradient zone and convective zone. As mentioned in Chapter I, a solar pond normally has three distinct zones, on top a surface convective zone, on bottom a lower convective zone, and a thick gradient zone in between. If the instability of the gradient occurs, as discussed in Chapter III, some internal convective zones may exist within the gradient zone. Therefore there are at least two gradient-convective interfaces in a solar pond.

In the gradient zone, both temperature and salinity increase downward and the transport process is dominated by microscopic molecular motion. In the convective zone, the transport of heat and salt results from mass
motion. The boundary between the convective zone and the gradient zone is characterized by a relatively sharp interface at a certain level in which the gradient changes rather sharply from a non-zero value to zero. This stationary boundary only can be maintained if there is a circulation in the convective zone of such a strength as to maintain the zone mixed and to balance the tendency of diffusion to enlarge the gradient zone. The general physical picture of the balance between gradient zone and convective zone has been discussed intensively by Nielsen [1] [2] [3].

In recent years, many observations have been made to describe some aspects of the boundary behavior in solar ponds. Within these observations, the best description of the conditions for growth and shrinkage of the gradient zone in NaCl thermohaline systems is given by Nielsen’s equilibrium criterion [4] [5]. It was found empirically that gradients both in laboratory tanks and at the boundaries of internal convective zones in outside ponds are fairly well correlated by the power law relation

\[ G_S = AG_T^{0.63}, \] (4.1)

in which A has the value \(28 (kg/m^4) (m/^\circ C)^{-0.63}\) when \(G_S\) is in \(kg/m^4\) and \(G_T\) is in \(^\circ C/m\). If the temperature gradient and salinity gradient close to the boundary satisfy Nielsen’s boundary criterion, a constant level of boundary can be maintained. The observations of gradient zone behavior in the ANL pond [6] and Miamisburg pond [7] also seemed well correlated by the above criterion.
Because erosion of the gradient zone at the boundaries is a common occurrence which tends to shrink the thickness of the gradient zone, consequently reduce the thermal performance of solar pond, research on the boundary behavior of solar ponds has been emphasized in recent years. In order to fully understand the details of zone interface processes, two major related questions which have often been asked are: (a) How are the heat and mass transferred through gradient-convective interfaces and what is the driving mechanism of the heat and mass transports? (b) If there is a transition region between gradient zone and convective zone, why can this transition region be kept stationary under certain temperature and salinity gradient conditions and what kind of dynamic processes are involved in the balance of the transition region?

4.1.2 Experimental Studies of Boundary Behavior

Some information about the behavior of the transition region and the nature of the circulation in the convective zone is provided by very high resolution temperature observations in laboratory tanks by Kamal and Nielsen [8]. Near the gradient-convective boundaries, the varying shape of temperature distribution and temperature fluctuations of tenths of a degree C were observed. In their experiments, with a convective zone on top of a gradient zone, the variations observed at different depth and the direction of the temperature peaks in each case showed that the circulation involves warm thermal plumes rising from the interface region and cold thermal plumes falling from the surface.
The sizes of these plumes are estimated to be $1 - 2\text{cm}$ with a characteristic generation period of minutes.

In another laboratory experiment conducted by Meyer et al \cite{9} at Los Alamos National Laboratory, a flow visualization technique showed plumes descending from the lower boundary of the gradient zone into the lower mixed zone with a velocity of the order of $2\text{mm/sec}$ and a horizontal spacing of $3 - 6\text{cm}$. Both ascending and descending plumes have been also observed in flow visualization experiments at Purdue University \cite{10} \cite{11} in which individual thermal plumes persisted for many minutes.

Another aspect of the boundary behavior that has been reported from different observations is that at a given horizontal location in a system near equilibrium, the temperature boundary often extends into the convective zone past the salinity boundary by about $1\text{cm}$ \cite{8} \cite{12} \cite{13} \cite{14}. While the salinity boundary remains relatively fixed in time, the apparent vertical position of the temperature boundary will experience fluctuations in time periods of the order of minutes \cite{8}. By shadowgraph technique, Mehta et al \cite{14} and Poplawsky et al \cite{15} have also observed a boundary layer of $5 - 30\text{mm}$ thickness which separates the diffusive core of the gradient zone from the adjacent convective zone.

4.1.3 Phenomenological Model of Boundary Structure

Based on the experiment observations and the studies on the convection above a rigid plate \cite{16} \cite{17} \cite{18} \cite{19}, Nielsen \cite{2} \cite{8} has proposed a qualitative
model of the structure of the boundary layer between gradient zone and convective zones in solar ponds. In this model when a convective zone is adjacent to a gradient zone, both heat and salt are being diffused from the gradient zone, and both a thermal boundary layer and a salinity boundary layer are created. The thickness of these layers is proportional to the square root of the corresponding diffusivity. Because salt diffusivity is of the order of one hundredth of thermal diffusivity, the salinity boundary layer develops to a thickness of the order of one tenth the thickness of the thermal layer over the same time period.

The convective heat transfer in the convective zone can be considered as the contribution of thermal plumes originating in thermal boundary layers which under solar pond conditions can reach of the order of one centimeter thickness. Until it becomes unstable and generates thermal plumes moving through the bulk fluid, the boundary layer is quiescent like the gradient and transfers heat only by conduction.

The thermal plumes rise and fall, moving with laminar flow, and by viscous drag set the intervening almost entirely isothermal regions into complicated and randomly varying slow circulation. This intervening fluid in time-varying slow circulation is merely the medium through which the plumes travel, while itself contributing very little either to the heat transfer or to the dynamic processes of boundary layers. A schematic of a circulation pattern of this model which consistent with all of the experiment observations is given by Nielsen [8] and is shown in Figure 4.1.
Figure 4.1: Schematic representation of circulation pattern in the convective zone of a solar pond which is consistent with all of the experiment observations (from C.E. Nielsen [8]).
Because the dynamic process in this model is contributed by the development of the boundary layer, this model is often called boundary layer model. The physical picture of the boundary layer model gives the right dependence upon the gradients but does not include any consideration of the kinetic energy of circulation. Witte and Newell [20] have developed an erosion model based on the diffusive phenomena described above, and their result for a stationary boundary yields a linear relation between $G_S$ and $G_T$, rather than the 0.63 power indicated in Nielsen's criterion (Equation 4.1). Therefore, their boundary layer model can not completely explain the balance of the transport processes at gradient-convective interfaces.

4.1.4 Other Theoretical Studies of Boundary Behavior

The suggestion being made is that there are two quite distinct processes involved in the balance necessary for stationary interfaces. One is the boundary layer process, which depends solely upon the salinity gradient and temperature gradient within the gradient zone, and not upon kinetic energy. This is purely a buoyancy-driven process, involving buoyancy potential energy resulting from heat transfer into the boundary layer. The other, is the process in which some of the kinetic energy of circulation is used to remove fluid elements out of the interface, overcoming their negative potential energy and resulting in interface erosion. Kinetic energy of circulation is transmitted to the interface by plumes rising from the bottom of the convective zone if a gradient zone is sitting on the top of a convective zone.
Entrainment of kinetic energy at gradient-convective zone boundaries has been studied by Bergman et al.\[21\] \[22\] \[23\] \[24\] \[25\]. In his one-dimensional multi-layer model, species and energy balances were applied to selected volumes of the convective zone and the gradient zone. Gradient zone erosion was represented by an entrainment velocity which correlated to the friction velocity associated with turbulence in the convective zone and a density jump at the zone boundary. This model was later developed into a differential model that incorporated a $\kappa - \epsilon$ model of turbulent entrainment \[22\]. Atkinson and Harleman \[26\] have also suggested a one-dimensional erosion model based on a correlation of entrainment of turbulent kinetic energy. The kinetic energy entrainment mechanism appears to dominate for certain conditions where gradient zone erosion is rapid.

Still other processes are certainly occurring at the interfaces, and a complete description is not yet available. For example, it is known that close to the interface the temperature in the gradient zone varies appreciably, with a characteristic time of minutes. Hull et al.\[27\] \[28\] have calculated the circulations within the gradient that are associated with these temperature variations and have related them to the interface balance. The calculations show that the temperature variations produce a microconvection that extends within the gradient zone over a spatial distance equivalent to what is observed experimentally. It is also known that the impingement of thermal plumes from a convective zone on a gradient zone boundary causes the boundary to become slightly uneven, and affects the development at the interface.
When incorporated into the microconvection model, this effect provides an improved physical understanding of erosion.

4.1.5 Objective of the Investigations

The previous observations and theoretical models have explained some aspects of the dynamic processes at the gradient-convective interfaces. However, there are still many fundamental questions involving the physical mechanisms of boundary behavior which are not very clear yet. Although some detailed temperature fluctuation [8] [12] and salinity fluctuation [13] measurements have been made in laboratory tanks to help obtaining a dynamic picture of the boundary layer, we have not seen any previous study in which the detailed simultaneous temperature and salinity fluctuations and the fine temperature and salinity structure at the gradient-convective interface has been recorded. It is our purpose in the laboratory tank experiments to investigate the fluctuations of both temperature and salinity at the gradient-convective interface, to study the detailed structure of temperature and salinity fluctuations, and to obtain further understanding of the dynamic mechanisms which govern the boundary behavior in solar ponds.

Simultaneous temperature and salinity fluctuation measurements at certain fixed positions within the gradient zone, around the gradient-convective interface and within the convective zone are made by using a thermocouple and a conductivity probe together. The characteristics of the fluctuations at different regions of the interface are investigated statistically. Vertical dis-
tributions of fluctuation amplitudes for both temperature and salinity fluctuation are plotted as r.m.s. profiles, the directions of the fluctuations are determined quantitatively by the means of third order moments calculations, and the frequency spectrum of the fluctuations is obtained by Fourier transform.

Temperature fluctuations at different vertical positions across the boundary layer are measured simultaneously to examine the structure of the interface. The correlation coefficient of simultaneous fluctuations at different regions is calculated to distinguish different processes. Also, short range temperature and salinity scans through the interface are used to obtain the instantaneous temperature and salinity profiles.

4.2 Simultaneous Measurements of Temperature and Salinity Fluctuation

4.2.1 Experimental Procedures and General Observations

Four runs of simultaneous measurements of temperature and salinity fluctuations within the gradient zone, across the gradient-convective interface and within the convective zone were performed in the laboratory tank as described in Section 2.2. In each experiment run, a gradient was set up and maintained using the techniques as mentioned in Section 2.3. The profiles were kept in a two zone configuration. Therefore, only one gradient-convective interface existed during all the experiment runs. Typical temperature and salinity
profiles around the interface are shown in Figure 4.2.

The bottom heating rate was adjusted to achieve a nearly stationary boundary position. The boundary movement was less than one centimeter per week which was slow enough to ensure the equilibrium condition in each experiment run. The experimental conditions including the temperature $T_C$ and salinity $S_C$ in the convective zone, the temperature gradient $G_T$ and salinity gradient $G_S$ in the gradient zone and the gradient zone thicknesses $h_G$ in each experiment run are listed in Table 4.1.

Table 4.1: The experimental conditions under which the temperature and salinity fluctuations were measured in each experiment run. In this table, $T_C$ and $S_C$ are temperature and salinity in the convective zone, $G_T$ and $G_S$ are temperature and salinity gradients in the gradient zone, and $h_G$ is the thickness of the gradient zone.

<table>
<thead>
<tr>
<th>Run#</th>
<th>$T_C(°C)$</th>
<th>$S_C(%)$</th>
<th>$G_T(°C/cm)$</th>
<th>$G_S(%)/cm$</th>
<th>$h_G(cm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>33.3</td>
<td>8.9</td>
<td>0.64</td>
<td>0.41</td>
<td>28</td>
</tr>
<tr>
<td>#2</td>
<td>34.0</td>
<td>8.5</td>
<td>0.67</td>
<td>0.47</td>
<td>25</td>
</tr>
<tr>
<td>#3</td>
<td>34.1</td>
<td>6.8</td>
<td>0.62</td>
<td>0.43</td>
<td>15</td>
</tr>
<tr>
<td>#4</td>
<td>33.6</td>
<td>6.1</td>
<td>0.58</td>
<td>0.39</td>
<td>14</td>
</tr>
</tbody>
</table>

The correlations of temperature and salinity gradient near the boundary which satisfy Nielsen's boundary criterion are plotted in Figure 4.3.
Figure 4.2: Mean temperature and salinity profiles around the gradient-convective interface in Experiment Run #2. These profiles give experimental conditions under which the temperature and salinity fluctuations were measured.
Figure 4.3: The correlation of temperature gradient $G_T$ and salinity gradient $G_S$ near the boundary. The solid line in this graph is Nielsen’s boundary criterion which is expressed as $\log G_S = 0.477 + 0.63 \log G_T$ where $G_S$ is in $\%/m$ and $G_T$ is in $^\circ C/m$. The measured values in each experiment run are shown as markers. The error bars which are only plotted on $\log G_S$ in this figure represent the measurement uncertainties which are estimated as $\pm 0.07^\circ C/cm$ and $\pm 0.04%/cm$ on $G_T$ and $G_S$ respectively.
One thermocouple and one conductivity probe as described in Section 2.4 were used and high resolution measurements were obtained. Data was taken every 3 sec in 10 min duration at each level. The measured temperature and conductivity signals were recorded by computer. Typical plotting of the temperature and salinity fluctuations at six different positions are shown in Figure 4.4 and Figure 4.5. If we define the average boundary position at \( z = 79 \text{ cm} \), these six positions are: (a) within the gradient zone, 10 cm above interface, (b) within the gradient zone, 1.5 cm above the boundary, (c) upper portion of transition region, at \( z = 79.5 \text{ cm} \), (d) within the transition region, at \( z = 78.75 \text{ cm} \), (e) lower portion of transition region at \( z = 78.5 \text{ cm} \), and (f) within the convective zone 1.5 cm below the boundary. In these figures, temperature and salinity are measured simultaneously at each position but in each figure the six traces were made at different time, so they are not correlated.

As shown in Figure 4.4 and Figure 4.5, the pattern of temperature and salinity fluctuation varies significantly at different regions. Within the gradient zone 10 cm above the average transition lever, the fluctuations of both temperature and salinity were very smooth and the amplitudes were less than 0.005°C and 0.001% for temperature and salinity respectively. The smoothness of both the temperature and salinity fluctuation traces within the gradient zone exhibits the low noise level of the measurement systems and gives confidence that the variations in the other traces are real and not significantly affected by instrumental limitations. When the measurement
Figure 4.4: The temperature fluctuations measured in Experiment Run #2 at different levels in and near the gradient-convective boundary. Each curve was taken at different time in this plot.
Figure 4.5: The salinity fluctuation taken simultaneously with temperature fluctuation in Experiment Run #2 as shown in Figure 4.4.
probes approached to the upper portion of the transition region from the gradient zone, the fluctuation became very large, as large as 0.5°C and 0.2%, with a tendency of positive changing. Further lowering the probes down to the lower portion of the transition region, negative temperature and salinity spikes with peak values of 0.3°C and 0.1% were observed. As the probes sat within the convective zone, the temperature and salinity fluctuations became small again.

These pictures show that a transition region with approximately 1.5 cm thickness exists at the gradient-convective interface. Within the transition region, large temperature and salinity fluctuation are found with entirely different characteristics at the upper portion and at the lower portion. These different characteristics of the fluctuations represent certain dynamic processes responsible for such boundary behaviors.

4.2.2 Comparison of Temperature Fluctuation and Salinity Fluctuation

It can be found very clearly by a brief comparison of the temperature and the salinity fluctuations plots that fluctuation patterns at each region are almost identical and follow each other in time, although the temperature fluctuation seems to die out more quickly than the salinity fluctuation does in the gradient zone near the gradient-convective interface. Detailed comparisons of the coincidence of temperature and salinity fluctuations are shown in Figures 4.6, 4.7, 4.8 and 4.9 which present the simultaneously measured
Figure 4.6: Simultaneously measured temperature and salinity fluctuation at $z = 80.5 \text{ cm}$ which is within the gradient zone and 1.5 cm above the average gradient-convective interface position. The correlation coefficient between two curves is 0.8.
Figure 4.7: Simultaneously measured temperature and salinity fluctuations at $z = 79.5\,cm$ which is within the upper portion of the gradient-convective interface. The correlation coefficient between two curves is 0.9.
Figure 4.8: Simultaneously measured temperature and salinity fluctuation at $z = 78.75\, cm$ which is within the transition region of the gradient-convective interface. The correlation coefficient between two curves is 0.93.
Figure 4.9: Simultaneous measured temperature and salinity fluctuation at $z = 78.5\text{ cm}$ which is within the lower portion of the gradient-convective interface. The correlation coefficient between two curves is 0.92.
temperature and salinity fluctuations at four different positions in and near the interface. It is shown that the temperature curve and the salinity curve in these plots are too similar to distinguish the difference except Figure 4.6. In Figure 4.6, the amplitude of temperature fluctuation decreases with distance from the interface more rapidly than the salinity fluctuation does but the general nature of the time variation remains similar.

The quantitative comparison of the temperature and salinity fluctuations can be made by calculating the correlation coefficient of each pair of simultaneous temperature and salinity measurements. The correlation coefficient is defined as follows,

\[ r = \frac{\sum_{i=1}^{n}(T_i - \overline{T})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(T_i - \overline{T})^2}\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}}, \]

where \( n \) is number of samples. In our calculations \( n = 200 \) is used.

The values of \( r \) for the simultaneously measured temperature and salinity fluctuations at the different positions shown in Figures 4.6, 4.7, 4.8 and 4.9 are presented in Table 4.2. All the correlation coefficients within the transition region are over 0.9. Within the gradient zone at 1.5 cm away from the average boundary position, although the details of the temperature fluctuation have died out, the correlation coefficient is still larger than 0.8. The excellent coincidence between the temperature fluctuation and the salinity fluctuation shows that the fluid motions involved in the boundary behavior are mass motions which can be either convective flow or bulk oscillation, and heat transport is always associated with mass transport in the dynamic processes that occur at and near the transition region.
Table 4.2: Correlation coefficient of temperature and salinity fluctuations at four different positions.

<table>
<thead>
<tr>
<th></th>
<th>80.5cm</th>
<th>79.5cm</th>
<th>78.75cm</th>
<th>78.5cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>0.80</td>
<td>0.90</td>
<td>0.93</td>
<td>0.92</td>
</tr>
</tbody>
</table>

4.3 Characteristics of Temperature and Salinity Fluctuations

4.3.1 Amplitude of Temperature and Salinity Fluctuations

The amplitudes of temperature and salinity fluctuations can be represented by $r.m.s.$ values. In our experiments, 200 samples separated by 3 sec were taken at each vertical position and the $r.m.s.$ fluctuations were calculated by using

$$\theta = \sqrt{\frac{1}{200} \sum_{i=1}^{200} (T_i - \bar{T})^2}$$

and

$$\sigma = \sqrt{\frac{1}{200} \sum_{i=1}^{200} (S_i - \bar{S})^2}$$

where $\theta$ is $r.m.s.$ fluctuation of temperature and $\sigma$ is $r.m.s.$ fluctuation of salinity.

The values of $\theta$ and $\sigma$ which represent the average magnitudes of the temperature and salinity fluctuations at each vertical position for all the experiment runs are plotted in Figures 4.10 and 4.11 along with the curves representing the general trends. In these figures, the positions of the bound-
Figure 4.10: The profile of r.m.s. temperature fluctuation $\theta$ as the function of height. The reference position in this figure is the position of boundary which is determined by salinity profiles. The positive direction is upward into the gradient zone and the negative direction is downward into the convective zone. In this figure, measurements from four experiment runs are plotted as different markers along with the curve representing the general trend.
Figure 4.11: The profile of r.m.s. salinity fluctuation $\sigma$ as the function of height. The reference position in this figure is the position of boundary which is determined by the salinity profiles. The positive direction is upward into the gradient zone and the negative direction is downward into the convective zone. In this figure, measurements from four experiment runs are plotted as different markers along with the curve representing the general trend.
ary as determined by salinity profiles are used as the reference positions. The positive direction is upward into the gradient zone and the negative direction is downward into the convective zone. It can be seen from these figures that the distributions of $\theta$ and $\sigma$ are almost identical. The r.m.s. value has a sharp peak within the transition region and decreases on each side. In both figures, the appearance of the peaks seems to be very symmetric with a characteristic band width of 1.5cm which can be interpreted as the average thickness of the transition region. This result is simply a way of characterizing the observations from the fluctuation plots in Figure 4.4 and Figure 4.5. In those plots, the maximum fluctuations occur within the transition region with 1.5cm thickness and die out very rapidly outside that region.

It is noted from Figure 4.10 and 4.11 that the peak r.m.s. value of temperature fluctuation appears at approximate 0.5cm below the salinity boundary while the peak r.m.s. value of salinity fluctuation appears almost at the boundary. A detailed comparison between temperature and salinity r.m.s. profiles in Experiment Run # 3 is shown in Figure 4.12 which is typical of the temperature and salinity r.m.s. distributions in all experiment runs.

In order to represent the fluctuation strength in thickness, the values of $\theta/G_T$ and $\sigma/G_S$ may be used as the fluctuation length scales. In our experiments the maximum values $\theta_{\text{max}}/G_T$ and $\sigma_{\text{max}}/G_S$ were found within the transition region and these values are listed in Table 4.3 for each experiment run. It is shown in this table that the average maximum temperature fluctuation length scale is 0.24cm and the average maximum salinity fluctuation
Figure 4.12: Detailed comparison between temperature and salinity r.m.s. profiles in Experiment Run #3 which is typical of the temperature and salinity r.m.s. distributions in all experiment runs. In this figure, the reference position has been shifted to the position of boundary which is determined by the salinity profile.
Table 4.3: Maximum temperature and salinity fluctuation length scales calculated for four experiment runs at the transition region of gradient-convective interface.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_{\text{max}} / G_T (cm)$</th>
<th>$\sigma_{\text{max}} / G_S (cm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>run #1</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>run #2</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>run #3</td>
<td>0.24</td>
<td>0.08</td>
</tr>
<tr>
<td>run #4</td>
<td>0.21</td>
<td>0.05</td>
</tr>
<tr>
<td>average</td>
<td>0.24</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The fluctuation length scales can be used to investigate the nature of the fluctuations within the gradient zone. If we calculate the fluctuation length scale at the position in the gradient zone near the transition region (say 1 cm from average boundary position into gradient zone), we can find that the values of $\theta_{1\text{cm}} / G_T$ and $\sigma_{1\text{cm}} / G_T$, which are listed in Table 4.4, are in agreement within 10% discrepancy. This result is as a consequence of the position shifting of peak values in $\theta$ and $\sigma$ profiles and consistent with the general observations from Figure 4.4 and Figure 4.5 in that the temperature fluctuation dies out much quickly than the salinity fluctuation does within gradient zone. Because the only fluid motion in the gradient zone can be assumed to be bulk fluid oscillation, the displacement of fluid element cal-
Table 4.4: Temperature and salinity fluctuation length scales calculated for four experiment runs within the gradient zone near the gradient-convective interface.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_{1em}/G_T(cm)$</th>
<th>$\sigma_{1em}/G_T(cm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>run #1</td>
<td>0.059</td>
<td>0.051</td>
</tr>
<tr>
<td>run #2</td>
<td>0.058</td>
<td>0.059</td>
</tr>
<tr>
<td>run #3</td>
<td>0.024</td>
<td>0.018</td>
</tr>
<tr>
<td>run #4</td>
<td>0.028</td>
<td>0.024</td>
</tr>
<tr>
<td>average</td>
<td>0.042</td>
<td>0.038</td>
</tr>
</tbody>
</table>

calculated from the temperature fluctuation is expected to be equal to that calculated from the salinity fluctuation, that is $\theta/G_T = \sigma/G_S$. Therefore, the nondimensional value $(\theta/\sigma)/(G_T/G_S)$ can be used for recognizing the oscillatory motion while $(\theta/\sigma)/(G_T/G_S) = 1$ represents the purely oscillation case. In Figure 4.13, the values of $(\theta/\sigma)/(G_T/G_S)$ in Experiment Run # 3 and Run # 4 are plotted as the function of height. It can be seen from this figure that in the region above the salinity boundary, the values $(\theta/\sigma)/(G_T/G_S)$ are close to 1 and in the region below the salinity boundary within the transition region, the values of $(\theta/\sigma)/(G_T/G_S)$ are much larger than 1. This result reveals that besides the purely oscillatory motion, there are other processes which are responsible for the boundary behaviors.
Figure 4.13: In this figure, the values of \( (\theta/\sigma)/(G_T/G_S) \) are plotted as the function of height for Experiment Run #3 and Run #4, and the reference position has been shifted to the boundary positions which is determined by the salinity profiles. The positive direction is above the boundary into the gradient zone and the negative direction is below the boundary into the convective zone. The vertical solid line in this plot gives the boundary position and the horizontal solid line in the gradient zone is \( (\theta/\sigma)/(G_T/G_S) = 1 \) which represent the purely oscillation case. The position at which the maximum value of \( \theta \) obtained is indicated as arrows in this figure.
4.3.2 Direction of Temperature and Salinity Fluctuations

More information of the dynamical processes near the transition region may be obtained by examining the vertical profiles of third-order moments [31]. The third order moments of temperature and salinity fluctuations can be defined as

\[
\bar{\theta}_3 = \sqrt[3]{\frac{\sum_{i=1}^{200} (T_i - \bar{T})^3}{200}}
\]

and

\[
\bar{\sigma}_3 = \sqrt[3]{\frac{\sum_{i=1}^{200} (S_i - \bar{S})^3}{200}}
\]

where \( \bar{\theta}_3 \) is the third-order moment of temperature fluctuation and \( \bar{\sigma}_3 \) is the third order moment of salinity fluctuation. The third order moments \( \bar{\theta}_3 \) and \( \bar{\sigma}_3 \) as the function of height are shown in Figures 4.14 and 4.15.

The measurements of \( \bar{\theta}_3 \) and \( \bar{\sigma}_3 \) are useful because their signs reveal the average direction of the relative temperature and relative salinity of moving fluid elements in that region. The third order moment is also helpful for distinguishing different physical processes. For example, if the fluid motion is a regular oscillation, the value of third order moment should be small since no significant direction tendency can be found.

In Figures 4.14 and 4.15, the reference positions are the position of the salinity boundary which is determined by the salinity profiles. Actual data points from four experiment runs are plotted as different markers, along with a curve representing trends in direction as a function of height. The third-order moments exhibit the same sort of variation in all experiment runs.
Figure 4.14: The third order moments of temperature fluctuation $\overline{\theta_3}$ calculated for four experiment runs are shown in this figure as different markers, along with a solid curve representing trend in direction as a function of height. The reference position in this figure is the position of the salinity boundary which is determined by the salinity profiles. The positive direction is upward into the gradient zone and the negative direction is downward into the convective zone.
Figure 4.15: The third order moments of salinity fluctuation $\sigma_3$ calculated for four experiment runs are shown in this figure as different markers, along with a solid curve representing read in direction as a function of height. The reference position in this figure is the position of the salinity boundary which is determined by the salinity profiles. The positive direction is upward into the gradient zone and the negative direction is downward into the convective zone.
although sampling errors are large. Hence, qualitatively these moments can be treated with confidence.

Figures 4.14 and 4.15 show that there are two sharp peaks just below $z' = 0$ in $\bar{\theta}_3$ and $\bar{\theta}_5$ profiles. These two peaks are anti-symmetric and within a region of $1.5\text{cm}$ which is consistent with the transition region we defined in Section 4.2.1 and Section 4.3.1.

In the region between $z' = -0.5\text{cm}$ and $-1\text{cm}$, the negative peak of $\bar{\theta}_3$ and $\bar{\theta}_5$ can be explained as the contribution of the generating and releasing processes of thermal plumes at the lower portion of transition region associated with large negative temperature and salinity fluctuations. The negative tendency last at least 3 centimeters extended into the convective zone. This is a characteristic of thermal plumes because if a cold thermal plume leaves the boundary layer and travels downward, negative fluctuation peaks should be detectable along the trace for a certain distance.

At $z > 1\text{cm}$, in the gradient zone, Figure 4.14 and 4.15 show both small positive and negative values of $\bar{\theta}_3$ and $\bar{\theta}_5$ around zero, meaning that the rising and falling fluid elements contribute equally. The oscillatory motion of fluid is active in such a way that the opposing statistical characteristics cancel out. This result is consistent with the result of fluctuation length scale analysis in Section 4.3.1 that within the gradient zone near the upper portion of the transition region, the nature of fluid motion is oscillation.

In the region between $z' = 0$ and $-0.5\text{cm}$, there is a positive peak with the same size as the negative peak in the region between $z' = -0.5\text{cm}$ and $-1\text{cm}$.
One of the possible explanations postulated to explain this positive peak is as follows. Based on the boundary layer model, if temperature and salinity sensors are positioned at the upper portion of the boundary layer, they may experience a gradual change in both temperature and salinity during the creating period of the thermal plume. However, when a cold thermal plume driven by a negative buoyancy force is released from the boundary layer, warmer surrounding fluid will occupy the vacancy associated with certain kinetic energy. Hence the temperature and salinity sensors will experience warmer and salty pulses which are responsible for the large temperature and salinity fluctuations with positive direction observed at the upper portion of the transition region. The schematic of this process is shown in Figure 4.16.

4.3.3 Characteristic Frequencies of Fluctuations

Because of the coincidence of temperature and salinity fluctuations, the characteristic frequencies are only measured for temperature fluctuations. Such measurements are made at two positions, near the upper portion of the transition region and near the lower portion of the transition region. Temperature fluctuation data are Fourier transformed thus yield the Fourier coefficients which give the frequency spectrum. The frequency spectra of temperature fluctuation at two different positions are given in Figures 4.17 and 4.18 respectively.

By evaluating Figure 4.17, we find that the successive lower peaks are at approximately integer multiple of the basic frequency in frequency spectrum
Figure 4.16: Schematic of the generation and breakoff processes of thermal plumes. In this figure, a gradient zone sitting on top of a warmer convective zone is assumed.
Figure 4.17: Frequency spectrum of temperature fluctuation at the upper portion of the transition region obtained by Fourier transform. The largest peak gives the characteristic frequency of 0.0033 Hz which corresponds to 300 sec characteristic period.
Figure 4.18: Frequency spectrum of temperature fluctuation at the lower portion of the transition region obtained by Fourier transform. The band width of the peak gives the range of characteristic period from 120 sec to 400 sec.
which may caused by a single highly non-sinusoidal oscillation. This result suggests an oscillatory nature of fluid motion, which agrees with the previous observations. Counting the largest peak in the frequency spectrum, the average value of the characteristic frequency at near the upper portion of the transition region is determined as 0.0033 Hz which corresponds to 300 sec characteristic period.

In contrast, in Figure 4.18, the bandwidth of the characteristic frequency is wider than in Figure 4.17 and the characteristic period at the lower portion of the transition region is dominated by a range of periods from 120 sec to 400 sec with short period associates.

These periods can be compared with the calculated value from the possible dynamic model. If there are thermal plumes generated from the boundary layer, the characteristic frequency of the temperature fluctuation near the boundary can be evaluated by applying Howard’s thermal burst model to our condition. Lindberg [32] has evaluated the breakaway time of thermal bursts for rigid horizontal planes which are permeable to heat and solute and in steady state. The equation for the characteristic period of temperature and salinity fluctuations at the boundary can be written as

\[ T^* = \pi \left( \frac{2R_{crit} \nu}{16 \frac{g \alpha \delta T \kappa_T}{\kappa_S} \left[ 1 - \left( \frac{\beta}{\alpha} \right) \delta T \left( \frac{\kappa_S}{\kappa_T} \right)^{\frac{1}{2}} \right]} \right)^{\frac{1}{2}}. \]  

In this equation \( R_{crit} \) is the threshold value of the thermal Rayleigh number, \( g \) is the acceleration of gravity, \( \alpha \) is thermal expansion coefficient, \( \beta \) is salinity expansion coefficient and \( \kappa_T \) and \( \kappa_S \) are diffusivity for heat and salt respectively. \( \delta T \) and \( \delta S \) are the temperature and salinity difference across
the boundary layer, and can be considered as the temperature and salinity fluctuations measured at the gradient-convective interface.

It is not obvious what value of $R_{\text{crit}}$ should be used. For different boundary conditions, this threshold is different [33]. Lindberg [32] used $R_{\text{crit}} = 1100$ in his calculation and Howard [18] suggested that for a thermal above a rigid plate $R_{\text{crit}} = 2650$. For free-free boundary conditions and a linear temperature gradient Chandrasekhar [34] has shown that $R_{\text{crit}}$ decreases to 657.5. However, if vertical displacement is allowed, this value is even larger than 2650 [35]. Since the gradient-convective boundary is a free-free boundary with possible vertical movement, $R_{\text{crit}} = 2650$ is used in our calculation.

The temperature difference across the boundary layer $\delta T$ can be estimated using the amplitude of the peak value of the temperature fluctuation at the lower portion of transition region. Because of the varying of the peak value of fluctuation amplitude from the observations, typically from 0.2°C to 0.4°C, the characteristic frequency varies and does not come out to be a single basic frequency. This can be explained as the result of initial conditions different for each individual thermal plume formation.

Inserting numerical values [30] for the properties appropriate to 34°C and 8.5%, which is the fluid temperature and salinity at the interface in Experiment Run # 2, and using the average value of salinity fluctuation which is 0.1%, then we calculate for maximum peak to peak temperature fluctuation $\delta T \sim 0.4°C$, $T^* = 112\text{sec}$, whereas for average temperature fluctuation $\delta T \sim 0.24°C$, $T^* = 400\text{sec}$. The values of calculated $T^*$ agree surprisingly
well with those observed in our experiments that are in the range from $120\,\text{sec}$ to $400\,\text{sec}$. This result supports Nielsen’s postulation of boundary layer mechanism at gradient-convective interface and the interpretation of the fluctuations at the lower portion of the transition region as attributable to the generation of thermal plumes.

4.4 Measurements of Spatial Structures of Fluctuations

4.4.1 Experimental Procedures

In Section 4.2, the temperature and salinity fluctuations were measured by a single fixed thermocouple and a conductivity probe. The traces shown in Figures 4.4 and 4.5 give the basic characteristics of the fluctuations at different regions but provide no information about the instantaneous spatial structures of temperature and salinity fluctuations at and near the gradient-convective interfaces because of no time relations between each measurement.

From the discussions in Section 4.3, it is clear that there are two distinct dynamic processes involved in the boundary behavior. Briefly, one is bulk fluid oscillations which produce the wavelike temperature and salinity fluctuation in the upper portion of the gradient-convective interface and produce vertical interface position oscillations which propagate into the gradient zone. Another is boundary layer processes which produce thermal plumes breaking away from the boundary layer and produce cell circulations in the convective
zone. As the result of these two effects, there is a transition region in between gradient zone and convective zone with a thickness of approximately 1.5cm.

In order to investigate the time relations of these two processes within the transition region and their effects on the vicinities, two methods were used in our experiments. First, the temperature fluctuations at three different positions were measured simultaneously by three fixed thermocouples with 1cm vertical separation. This array of thermocouples can be moved up and down. At each position, the measurement duration is 200sec with the sampling rate of 1sec.

A second way to obtain information about spatial structure is to make a short range temperature and salinity scan, which has been discussed in Section 2.4, through the transition region. The scan rate is 12cm/min which gives a total scan time of 20sec for 4cm vertical traversing distance. Comparing the characteristic fluctuation time of the order of 100sec, we see that instantaneous temperature and salinity profiles obtained by scan can be assumed over such short distance.

4.4.2 Temperature Structures in Vicinities of Transition Region

It has been shown in Section 4.2.2 that there is an excellent coincidence between the temperature fluctuations and salinity fluctuations. Therefore only temperature structures are investigated in this section. The simultaneous temperature fluctuations at three levels with 1cm separation were measured within the gradient zone near the transition region and within the convec-
tive zone near the transition region respectively. The typical measurement results are shown in Figure 4.19 and Figure 4.20. The characteristics of the temperature structure in these two regions are very different which reveal the information about different physical processes involved in each region.

In the convective zone, both shape and amplitude of the fluctuations taken at different levels are correlated in time. The temperature structure within 2cm to 3cm below the transition region can be described as the simultaneously appearing negative temperature spikes with almost the same amplitude. This spatial structure of the temperature fluctuation is the result of moving fluid elements with relative lower temperature than surrounding which can be interpreted as either the thermal plume moving vertically or the whole convective cell moving horizontally.

In the gradient zone, the characteristics of the temperature fluctuation structure are different from in the convective zone. It is shown in Figure 4.20 that the amplitude of the fluctuation within the gradient zone decays very rapidly in 2cm above the transition region although the trend of the fluctuation remains the same. This is the general characteristic of a mechanical wave propagated through the water in which the intensity of the wave is damped by fluid viscosity. The maximum peak to peak value of the temperature fluctuation of the order of 0.3°C which corresponds to the position displacement of the order of .05cm is reduced to 1/100 of its original value within less than 2cm. Therefore, the temperature fluctuation structure in the gradient zone can be characterized by a fast decay of temperature oscillation
Figure 4.19: The simultaneous temperature fluctuation measurements taken at three different vertical positions with 1cm separation within the convective zone just below the transition region.
Figure 4.20: The simultaneous temperature fluctuation measurements taken at three different vertical positions with 1cm separation within the gradient zone just above the transition region.
within a short distance.

**4.4.3 Temperature Structure of Transition Region**

The temperature structure in the transition region of the gradient-convective interface is much more complicated than that within the gradient zone or within the convective zone. This complication has been revealed in Figures 4.4 and 4.5 in which the characteristics of the fluctuation are totally different between upper portion and lower portion of the transition region. In the upper portion of the transition region, the fluid motion mainly is the bulk oscillation which propagates into the gradient zone, and makes an oscillatory temperature structure in the gradient zone as shown in Section 4.4.2. In the lower portion of the transition region, the fluid motion is the generating or releasing of thermal plumes which is the result of instability of boundary layer. Consequently the temperature structure in the convective zone near the transition region is characterized by intermittent negative temperature spikes; see Section 4.4.2. Hence, the temperature structure of the transition region should be affected by both motions.

The detailed temperature fluctuation structure of transition region has been studied by placing three thermocouples with 1 cm separation in the transition region since we know that the thickness of the transition region is 1.5 to 2 cm. The temperature fluctuation at up portion, center and lower portion of the transition region are measured simultaneously. The typical measurement results are shown in Figure 4.21.
Figure 4.21: Temperature fluctuation structure of transition region. In this figure, three thermocouples are placed vertically within the transition region with 1cm separation. The measurements were taken simultaneously.
Table 4.5: The cross correlation coefficients between the temperature fluctuation at lower, center and upper portion of the transition region. In the subscripts, $L$ stands for lower, $C$ stands for center and $U$ stands for upper.

<table>
<thead>
<tr>
<th>$\tau_{L-C}$</th>
<th>$\tau_{U-C}$</th>
<th>$\tau_{L-U}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.59</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The basic characteristic to be found in Figure 4.21 is that the fluctuations at upper portion and lower portion do not fluctuate simultaneously. This result means that these two fluctuations are active individually and joined by a certain mechanism which makes a connection between different temperature structures. A comparison of the temperature fluctuations at each portion of the transition region can be made by calculating the cross correlation coefficients between them, which are listed in Table 4.5. It is found that the correlation coefficients between center and edges of the transition region are larger than that between each edge by a factor of 3. This result suggests that the temperature structure of transition region is dominated by the effect of overlapping of fluid oscillation and instability of boundary layer, and may be the superposition of the temperature structures of its vicinities.

From the temperature structure of the transition region and the fact of opposite direction in the fluctuations at each edge, it can be postulated that the large oscillations at the upper portion of the transition region may be caused by the stimulations of the break off thermal plumes and the returning
fluid with kinetic energy from the lower convective zone. The characteristic frequency and the phase of the oscillation is not necessarily the same as the break off period of thermal plumes. At the transition region, the mass and energy are transferred by the joint effect of fluid oscillation and the instability of the boundary layer.

4.4.4 Instantaneous Temperature and Salinity Profiles of Transition Region

Another method to study the temperature and salinity structure is to investigate the instantaneous vertical temperature and salinity profiles through the transition region which were obtained by a short range temperature and salinity scan. Because either the bulk fluid oscillation or the break off of thermal plumes has a characteristic period in the order of couple minutes, if scans are taken successively, the variation in shape between the profiles is expected. The three sets of typical instantaneous temperature and salinity profiles are shown in Figures 4.22, 4.23 and 4.24 in which the temperature and salinity were measured simultaneously.

The general comparison between temperature profiles and salinity profiles of these plots shows that although the temperature profiles have significant variation in shape within the range of up to 1.5cm between scans, the salinity profiles remain almost the same. This result is consistent with the observations from outside solar ponds and also consistent with our boundary temperature and salinity fluctuations observations in which the temperature fluctu-
Figure 4.22: The instantaneous temperature and salinity profiles at the transition region and its vicinity. A relative sharp boundary of the temperature profile shows the quiescent period of the fluctuations.
Figure 4.23: The temperature and salinity profiles at transition region and its vicinity during the generation period of the thermal plume. A diffusive temperature boundary layer is developed with the layer thickness of 1 cm extended into the convective zone.
Figure 4.24: The temperature and salinity profiles at transition region and its vicinity. A temperature peak at the boundary is the result of the breakoff process of thermal plumes and the associated temperature oscillation.
ation is much larger than the salinity fluctuation at the gradient-convective boundary.

In Figure 4.22, the temperature profile has a relative sharp boundary as the salinity profile. This picture is the reflection of the quiescent period of temperature and salinity fluctuation and means that the ending of the breakoff process and the beginning of a new thermal plume generation in the boundary layer model.

In Figure 4.23, a developed diffusive boundary layer is observed significantly in temperature profile with the layer thickness of 1 cm extended into the convective zone while the salinity profile changes little. The breakoff process of thermal plumes and the associated temperature oscillation in gradient zone can be seen in Figure 4.24. In this figure, there is a temperature peak at the gradient-convective boundary. Similar observations have been reported by Kamal and Nielsen [8]. This peak can be explained as the result of the temperature oscillation near the gradient zone stimulated by the breakoff process of the thermal plumes while the gradient-convective boundary is recovered back to its original place. This temperature structure gives the erosive nature of the gradient-convective boundary which is dominated by the breakoff process of the thermal plumes. The discontinuity of the temperature gradient at the peak is physically impossible produced by one dimensional heat conduction. Its existence demonstrates conclusively the occurrence of lateral convective flow in the transition region.
The observations from the successive short range scans confirm the predictions of Nielsen's boundary layer model in that the thermal plumes are initiated as the instability of a diffusive temperature boundary layer, and provide a picture of the development of the boundary layer which is represented as the soft boundary between gradient zone and convective zone in the instantaneous temperature profile.

4.5 Summary and Discussion

In this chapter the fluctuations of temperature and salinity in and near the gradient-convective interface have been examined by simultaneous temperature and salinity measurements at different vertical position. Then, the statistical characteristics of the fluctuations are obtained along with the figures representing the typical appearance of the fluctuations at different region. In order to investigate the instantaneous spatial structures of interface temperature and salinity fluctuations, a vertically spaced thermocouple array and short range temperature and salinity scans are used to measure the simultaneous temperature fluctuation in space and the instantaneous vertical property profiles. These experiment observations and results are summarized as follows.

(1) There is a transition region with approximately 1.5cm thickness at the gradient-convective interface. Large temperature and salinity fluctuation \( \delta T > 0.5^\circ C \) and \( \delta S > 0.15\% \) were found with entirely different characteristics at the upper portion and at the lower portion of the transition region.
An excellent coincidence exists between the temperature fluctuation and the salinity fluctuation with the correlation coefficients larger than 0.9.

(2) The r.m.s. profiles of fluctuations were found to have a maximum, \( \theta_{\text{max}} = 0.15^\circ C \) for temperature and \( \sigma_{\text{max}} = 0.04\% \) for salinity, within the transition region, and to decrease rapidly on either side of the interface. The position of the maximum r.m.s. temperature fluctuation extended into the convective zone past the position of the maximum r.m.s. salinity fluctuation by approximately 0.5 cm.

(3) The fluctuation length scales were defined as \( \theta/G_T \) and \( \sigma/G_T \) to represent the effect of the fluctuation in space. It was found that in the transition region, the temperature fluctuation length scale was \( \sim 3 \) times larger than the salinity fluctuation length scale, whereas in the gradient zone these two length scales were compatible.

(4) The third order moment \( \bar{\theta}_3 \) and \( \bar{\sigma}_3 \) profiles were found to have a positive maximum and a negative maximum in the upper and lower portion of the transition region respectively within 1.5 cm thickness and have a discontinuity in between. These peaks represent the fluctuation tendency in direction and are consistent with the visual evaluation of the fluctuation curves.

(5) The characteristic periods of the fluctuations at the upper and lower portion of the transition region were found to be 300 sec and to range from 120 sec to 400 sec respectively by the means of Fourier transform. The range of characteristic fluctuation frequencies at the low portion of the transition region agrees surprisingly well with the results calculated by Lindberg's for-
mula [32] from a boundary layer model which are in the range from 112 sec to 400 sec.

(6) The simultaneous measurements of temperature fluctuation at different positions within the gradient-convective interface have revealed the oscillatory nature at the upper portion of the transition region and the boundary layer nature at the lower portion of the transition region. The fluctuations at each portion were not directly correlated and it might be a superposition of the two different effects at the center of the transition zone.

It was shown from these experiment results that there are two distinct dynamic processes involved in the boundary behaviors. One is the boundary layer process at the lower portion of the transition region and another is the bulk fluid oscillation at the upper portion of the transition region. The overlapping of these two processes constructs a core of the transition region at the center.

At the lower portion of the transition region, the experiment results on the temperature fluctuation support Nielsen’s boundary layer model of the gradient-convective interface in solar ponds in which the convective heat and mass transfer in the convective zone can be considered as the contribution of thermal plumes originating in a thermal boundary layer. The generating and breakoff processes are the origin of the temperature and salinity fluctuations at that region and the fluctuations are characterized by intermittent negative temperature and salinity spikes along the vertical distance for a couple of centimeters.
At the upper portion of the transition region, the bulk fluid oscillation produces the wavelike temperature and salinity fluctuations and propagates into the gradient zone with rapid decrease of amplitude. The temperature and salinity fluctuations in this region are both characterized by a decay of amplitude within a short distance.

The large oscillation with positive tendency in direction at the upper portion of the transition region may be the result of stimulation by the break off thermal plumes and the returning warmer fluid. The characteristic period and the phase of the oscillation are not necessarily the same as for the thermal plume break off. At the transition region, heat and mass are transferred by the joint effects of the fluid oscillation and the instability of the boundary layer.

The structure of the temperature and salinity fluctuation at the gradient-convective boundary investigated above is only one dimensional and provides no information about the wave length of the oscillation as well as the size and the horizontal movement of the convection or cells. The positive temperature fluctuation tendency at the upper portion and the negative temperature fluctuation tendency at the lower portion cause a peak in the instantaneous temperature profile within the transition region. The discontinuity of the temperature gradient at the peak reveals the possible existence of a local lateral convective flow. To solve this puzzle, a two dimensional study is recommended.
References


CHAPTER V

Effects of Surface Temperature Cycling on Surface Zone Creation and Growth

5.1 Introduction

5.1.1 Surface Zone Behavior

The internal stability of the gradient zone and the behavior of the interface between gradient zone and convective zone have been studied in Chapter III and Chapter IV. In these studies, the dynamic processes involved in the instability are purely affected by the steady internal heat and salt transfer from the bottom. However, at the free surface of water in solar ponds, the dynamic processes involved in the creation and growth of the surface convective zone are strongly influenced by the external environment, involving wind, insolation, evaporation, rainfall, ice formation as well as the ambient temperature variations. All these seasonal, daily, and intermittent effects are combined together to make the surface zone behavior of solar ponds very complicated. The effects of those combined external influences upon the pond surface have been reviewed by Nielsen [1] [2] [3] intensively.
It has been found that the most important erosive effects causing the surface zone creation and growth are wind mixing, evaporation and surface temperature cycling. The wind mixing is a mechanical process while the others are thermal processes.

For the wind mixing, Nielsen [4] has observed in the OSU 400m² pond that a mean squared wind speed in the range of $10-20 m^2/s^2$ induced observable gradient zone erosion while mean squared wind speed exceeding $20 m^2/s^2$ caused rapid erosion. The patterns of wind-induced circulation have been observed by Nielsen [4] in outside ponds and by Atkinson and Harleman [5], and Twede et al [6] in laboratory wind tunnel experiments. Meanwhile, some theoretical studies of the wind mixing on the surface have been carried out by Atkinson and Harleman [7], and Schladow [8]. By applying the results from oceanography and limnology, Schladow [9] has found that the relative importance of the wind mixing and thermal driven processes is very site-dependent and in some circumstances the dominant process is thermal convection.

It has been postulated that convection results from the formation of a gravitationally unstable layer on the surface which can be attributed to two district processes: salinity increasing on the surface or temperature variation. In both cases, heavier fluid on top will generate a surface convective zone, and also the released potential energy will be converted to turbulent kinetic energy which will push the surface-gradient convective boundary downward.
The salinity increasing at the surface is due to the contributions of the salt diffused from the gradient zone and the concentration by evaporation. The salinity increasing on top will produce or enhance the surface convection resulting in an erosive effect. Taking the consideration of the requirement for continuity of salinity, if the salinity in the surface convective zone increased the surface convective-gradient zone boundary must move down to the level where the salinity in the gradient zone matches the increased salinity in the surface zone [3]. However, these salt deposit phenomena are very complicated; sometimes they perform the opposite effect. Golding and Nielsen [10] have observed that following periods of surface evaporation the salinity gradient was extended upward for distances up to 10cm at the OSU solar pond.

The surface temperature variation results from the surface heating and cooling cycling which is considered as the combined influence of ambient temperature, insolation and evaporation. The effect of surface temperature cycling has been described qualitatively by Nielsen [1] as the origin of the surface convection if the wind mixing is excluded. Also, Nielsen [3] pointed out that a non-steady thermal convection produced by temperature cycling of the surface is more erosive than steady thermal convection associated with the same average heat transfer rate because of a nonlinearity in the relation between heat transfer and erosion.
5.1.2 Characteristics of Surface Temperature Variation in Solar Pond

To understand how surface temperature cycling can affect the surface zone creation and growth, the characteristics of surface temperature variation in outside solar ponds must be examined. The steady state temperature distribution in solar ponds has been calculated by Rabl and Nielsen [11] and Weinberger [12] for predicting solar pond thermal performance. In their calculation model, the insolation and the ambient air temperature both have a constant term and a sinusoidal term. Since the surface temperature strongly depends on the insolation and ambient temperature, if we applied their assumption in our case, the surface temperature variation can be also described as a constant term and a sinusoidal term

\[ T_s(t) = \bar{T}_S + T_0 \sin \omega t. \]

In this expression, \( \omega \) is the temperature variation frequency, for annual change \( \omega = 2\pi/\text{year} \), for daily change \( \omega = 2\pi/\text{day} \), and for sudden change, the variation can be Fourier decomposed and \( \omega \) can be taken as the basic characteristic frequency. For a given period, \( \bar{T}_S \) is the average surface temperature and \( T_0 \) is the amplitude of the surface temperature variation.

Consider the simple case in which a pond is maintained entirely nonconvective with a constant temperature gradient in it and is subject to surface temperature variation only. The one dimensional result of temperature dis-
tribution in the pond then can be expressed as [13]

\[ T(z', t) = \bar{T} + G_T z' + T_0 e^{-\sqrt{\frac{\kappa_T}{2\kappa_T z'}}} \sin(\omega t - \sqrt{\frac{\omega}{2\kappa_T}} z'), \quad (5.1) \]

where, \( z' \) is the depth counting from the surface, \( G_T \) is a positive value which corresponds to temperature increasing downward, \( \omega \) is the angular frequency of the surface temperature variation, and \( \kappa_T \) is the thermal diffusivity of the solution which is \( 1.5 \times 10^{-3} cm^2/sec \) typically.

The first term in Equation 5.1 is a constant gradient term which represents the steady heat transfer of the gradient zone. The second term is the oscillation term which gives the temperature variation at any depth in the pond. The amplitude of temperature variation is

\[ T_0 e^{-\sqrt{\frac{\kappa_T}{2\kappa_T}} z'}, \]

which has a maximum value at the surface where \( z' = 0 \) and decays exponentially with depth. The characteristic depth of the penetration of the surface temperature variation is defined as the depth at which temperature variations with frequency \( \omega \) damp to \( 1/e \) of their surface value, that is \( \sqrt{2\kappa_T/\omega} \).

For annual surface temperature variation, this value is \( 90cm \), and for daily surface temperature variation it is approximately \( 5cm \). This result shows that the effect of daily surface temperature variation may be negligible at the depth over \( 10 - 20cm \).

The distribution of temperature gradient with depth can be obtained from the first derivative of Equation 5.1, which is
where $\epsilon$ is a phase angle. The maximum temperature gradient occurs at the surface and is proportional to the square root of the temperature variation frequency. If we take the amplitude of daily surface temperature variation one fifth of annual surface temperature variation, the amplitude of variation in temperature gradient by daily surface temperature variation will still be 4 times larger than that by annual surface temperature variation because of the frequency dependence. This result tells us that a large temperature gradient variation may be produced by a very rapid surface temperature change even the absolute temperature variation is not very large. From the gradient instability of view, if the temperature gradient at the surface passes a certain value, a convective layer will be produced. Therefore, the effect of long period surface temperature variation, such as annual variation, on the surface stability is small and the thermal driven processes at the surface are dominated by the short period surface temperature variations.

5.1.3 Objectives of Investigation

The complication of the surface zone behavior has been discussed in previous sections. Various influences, including wind, salinity increase from evaporation and diffusion, and temperature cycling at the surface are recognized as the most important effects relevant to the creation and growth of the surface convective zone. Although some theoretical studies have predicted that the
cooling on surface may produce the surface convection [14] and may be more important than wind effect in some circumstances [9], however, it is still not well known what is the role of the temperature cycling individually acting on the surface.

Experimentally, there are various pieces of evidence [15] [16] showing the importance of non-steady thermal convection on the erosion of the gradient. However there is only one direct evidence which is provided by an experiment conducted by Nielsen [17]. In his experiment, two identical small solar ponds were operated with as nearly as possible identical salinity and temperature gradient and with 15 cm surface zones on both. Polyethylene film covers on both were submerged below the water surfaces at different depth in each tank. Wind effects were thus completely excluded from both and the daily washing just under the plastic covers maintained the surface zone at low density. It was found that under the deeper cover the mixed zone disappeared within three weeks, while under the shallower cover the zone boundary level was nearly constant, with the mixed zone remaining. The interpretation of these observation has been described as the influence of thermal cycling, the temperature variation being less under the deeper cover because the thicker layer of water above the cover supplied the greater heat capacity.

Besides Nielsen’s experiment, we have not found any previous studies in which detailed experimental investigations on the effect of surface temperature cycling have been conducted either in outside pond or in laboratory tank. The main reason for this is the difficulty to separate each individual
effect since the three major effects on surface behavior are usually associated together especially in outside ponds.

In our laboratory tank experiment, we have created an environment in which the effects of wind mixing, evaporation and salt diffusion can be ignored. Under this condition, we attempt to investigate the behavior and characteristics of the surface convective zone creation and growth by surface temperature cycling. These dynamic processes on surface convection driven by surface temperature cycling are then compared with the internal instability and boundary processes discussed in previous chapters to enhance our understanding of the inherent relations between each other.

5.2 Experiment Conditions and Test Procedures

5.2.1 Experiment Conditions

As discussed in Section 5.1, there are three most important effects, wind mixing, salt deposit on surface and surface temperature cycling, which are responsible for the surface zone creation and growth. In order to investigate the surface behavior produced by surface temperature cycling only, it is necessary to reduce the other two important effects as completely as possible. In our laboratory experiment, the test apparatus is so designed that the wind mixing, evaporation and salt diffusion are well controlled and under certain conditions, these effects can be ignored.
The general description of the test apparatus is given in Section 2.2. The more detailed discussions concerning the control of salt deposit on surface and the surface wind mixing are described as follows.

The salt deposit on surface can be attributed to evaporation on surface and the diffusion from bottom. In our experiment apparatus, the tank was covered by an air flow distributor as described in Section 2.2.3. The air on surface was withdrawn by a fan, then went through the heating and cooling elements and flowed back to the tank. This closed air circulation reduced the surface evaporation a great deal, therefore reduced the effects of evaporation. This argument is confirmed by measuring the overflow rate of surface wash. During the surface cooling and heating cycling, the overflow rate was found to be almost the same even when the surface temperature was very high. The surface wash was the most important procedure to remove the salt deposit both by diffusion and by evaporation on the surface. The surface wash with a rate of 9 liters per day was conducted continuously to maintain a low surface salinity. The fact of an almost constant salinity at surface monitored during entire experiment provided an experimental evidence that the effect of salt deposit was negligible.

Since the air that blew over the water surface served as the heat transfer medium in our surface temperature cycling experiment, the main consideration of the experiment conditions is to avoid any wind mixing on the surface. The major contribution for reducing the wind effect is made by using the special designed air flow distributor which has been discussed in Section 2.2.3.
Through the air flow distributor, the air flow became very smooth. This slow and smooth air flow was maintained on the surface during the entire laboratory experiments including the experiments we discussed in previous chapters. Since we did not observe any recognizable surface mixing by the air flowing over the water surface, it was experimentally verified that the wind effect can be neglected.

Further confirmation can be made by evaluation of the speed of the air flow. It is difficult to obtain the air flow rate directly since it is too slow to measure. However, the air flow rate can be estimated using heat balance equation if we know the temperature differences.

Consider a thin surface layer with a thickness of $\Delta z$; the balance of heat loss and heat gain on this layer during a certain time interval $\Delta t$ can be written as

$$Q = Q_\text{G} + Q_\alpha + Q_\text{w} + Q_\varepsilon,$$

(5.3)

where $Q$ is the heat to increase the surface layer temperature, $Q_\text{G}$ is the heat transferred into the layer from gradient zone, $Q_\alpha$ is the heat transfer due to air flow, $Q_\text{w}$ is the heat carried by surface wash and $Q_\varepsilon$ is the heat loss by evaporation. In this expression, the heat transfer by radiation is ignored since the tank is fully covered.

As discussed in Section 2.3.2, the heat carried out by surface wash is less than 2% of the heat transferred from the gradient zone, and the evaporation rate is also very slow. Therefore, the terms $Q_\text{w}$ and $Q_\varepsilon$ are small compared
with others and can be neglected. Then Equation 5.3 can be expressed as

\[ Q = Q_g + Q_a, \]  

(5.4)

where

\[ Q = A \cdot \Delta z \cdot \rho \cdot C \cdot \Delta T, \]  

(5.5)

\[ Q_g = A \cdot K \cdot G_t, \]  

(5.6)

\[ Q_a = B \cdot v_a \cdot \Delta t \cdot \rho_a \cdot C_a \cdot \Delta T_a. \]  

(5.7)

In this expression, \( A \) is the surface area, \( B \) is the cross section of air flow path, \( \rho \) and \( C \) are density and heat capacity of water, \( \rho_a \) and \( C_a \) are density and heat capacity of air, \( \Delta z \) is the layer thickness, \( \Delta T \) is the temperature change of the surface layer during the time interval \( \Delta t \), \( \Delta T_a \) is the temperature difference of air between air inlet and air outlet, \( K \) is the thermal conductivity of water, \( G_t \) is the temperature gradient in the gradient zone, and \( v_a \) is the speed of air flow. By inserting Equation 5.5 through 5.7 into Equation 5.4, the speed of air flow can be obtained as

\[ v_a = \frac{A \cdot \Delta z \cdot \rho \cdot C \cdot \Delta T - A \cdot K \cdot G_t}{B \cdot \Delta t \cdot \rho_a \cdot C_a \cdot \Delta T_a}. \]  

(5.8)

In our experiment apparatus, \( A \) is 4500 cm\(^2\), \( B \) is approximately 650 cm\(^2\). During the heating period, the typical values taken from our experiment data are \( \Delta z = 4 \text{ cm} \), \( \Delta T = 1 \text{°C} \), \( \Delta T_a = 10 \text{°C} \), \( G_t = 0.5 \text{°C/cm} \) and \( \Delta t = 1800 \text{ sec} \). Using property values [18] as \( \rho_a = 1.18 \times 10^{-3} (g/cm^3) \), \( C_a = 0.24 (Cal/°C \cdot g) \), \( \rho = 1(g/cm^3) \), \( C = 1(Cal/°C \cdot g) \) and \( K = 1.5 \times 10^{-3} (Cal/cm \cdot sec \cdot °C) \), the air flow speed is estimated to be 6 cm/sec. The mean squared value
of the air flow speed therefore is very slow and in the order of $0.01 m^2/s^2$ which is far below the critical mean squared value of $10 m^2/s^2$ observed by Nielsen in outside pond, and much below the minimum wind speed which is $\sim 0.5 m/s$ given by Kahma and Donelan [19] to produce the water wave on surface. This estimation provides another evidence that the wind effect can be neglected at such slow air flow speed.

5.2.2 Test Procedures

The surface temperature cycling was performed in two experiment runs. The objective of the first experiment run is to investigate the effect of surface temperature cycling on the surface convective zone creation and the objective of the second experiment run is to investigate the effect on the surface convective zone growth of surface temperature cycling. The surface heating and cooling procedure has been discussed in Section 2.2.3 in general. Since we know that the variation of the surface temperature gradient strongly depends on the frequency of the surface temperature variation, the period of the surface temperature cycling was adjusted to approximately 24 hours which corresponds to the daily ambient temperature variations and the heating and cooling processes were so controlled that the variation of surface temperature was almost sinusoidal.

During the heating/cooling cycling, the temperature and conductivity scans were made at each half hour to obtain the temperature and salinity profiles. In both experiment runs, the temperature and conductivity scans
were along the vertical line of the center of the tank and the scan distance was to 20cm from the water surface because the emphasis in these experiments was on the surface behavior and the surface temperature variation could not penetrate very deep; see Section 5.1.2. Besides temperature and conductivity scans, salinity samples were also taken regularly to confirm the results from scans and to serve as the standard for conductivity probe calibration. During the first experiment run, a rank of fixed thermocouples were mounted near the surface to measure the temperature oscillation at the onset of surface convection.

5.3 Creation of Surface Convective Zone by Surface Temperature Cycling

5.3.1 Initial Conditions and Penetration of Surface Temperature Cycling

Under the experimental conditions described in Section 5.2, a surface heating/cooling cycling experiment was conducted to investigate the process of surface convective zone generation. At the beginning of the experiment, there is a gradient zone on top of a convective zone and there is no surface convective zone of any significance. The upper portions of the initial temperature and salinity profiles are shown in Figure 5.1. This two zone configuration was maintained and the salinity profile was observed not to change significantly during the surface temperature cycling until the surface convective zone was
Figure 5.1: The initial temperature and salinity profiles taken at the beginning of the experiment. It can be seen from this figure that there is no surface convective zone of any significance initially. Some unevenness on salinity profile is due to the fast injection made within the gradient zone near the surface three days before, and some unevenness may be due to the measurement uncertainties.
The heating power at bottom was retained at 30W to supply a constant heat source for keeping a steady heat flux through the gradient zone, and for maintaining an equilibrium position of the lower gradient-convective boundary. The local stability margin numbers introduced in Section 3.2 were calculated through the whole gradient region. The results shown in Figure 5.2 show that the salinity gradient met the internal stability requirement anywhere within the gradient zone in which a steady heat flux was conducted. The smallest stability margin number found at 5cm below the surface was 3.3 which was still far above the internal stability criterion.

The surface heating/cooling cycling were performed in a period of approximately 24 hours. The surface temperature was heated up during the first 12 hours and then cooled down during another 12 hours. The heating and cooling processes were so controlled that the variation of surface temperature was almost sinusoidal. The peak to peak amplitude of surface temperature variation for the first complete cycle was 14°C. This value was increased to 23°C during the second complete cycle. The temperature variation at the surface for these two complete heating/cooling cycles is presented as the solid curve in Figure 5.3. The temperature variation at 4cm below the surface and at 10cm below the surface are also plotted in Figure 5.3 as different dashed lines. The amplitude decay and the phase lag of the propagation of surface temperature variation agree with the theoretical predictions which we discussed in Section 5.1.2.
Figure 5.2: The stability margin calculations for the initial temperature and salinity gradient. The fact that safety numbers are larger than 3.3 anywhere represents a stable gradient zone.
Figure 5.3: Penetration of surface temperature cycling into the gradient zone. In this figure, the solid line presents the temperature variation at surface, and the dashed lines are the penetrated temperature variation at 4 cm and 10 cm below the surface respectively.
5.3.2 Observations of Surface Convective Zone Creation

The observations of surface convective zone creation were obtained by the temperature and conductivity scans which were taken each half hour to monitor the temperature distributions during the heating/cooling cycling. A special attention was called when the temperature gradient reached the maximum. During this period the conductivity profiles were plotted out for assisting to realize the appearance of the surface convective zone. The typical plots showing the time development of the temperature profiles are given in Figure 5.4 and Figure 5.5 for the first complete cycle and for the second complete cycle respectively. It is noted that the envelope of the curves in each figure represents the exponential decay in depth of the surface temperature cycling penetration which has been discussed in Section 5.1.2.

In Figure 5.4, it is shown that there is not any evidence of surface mixing during the first cycle even though the maximum temperature gradient at surface has reached to 160°C/m. The amplitude of surface temperature variation was increased in the second cycle. During the cooling period, the surface convective zone was created within half hour; see Figure 5.5. A short dashed line in Figure 5.5 presents the temperature profile taken 0.5hr before the surface convective zone was created. The curve was smooth and the maximum temperature gradient was found to be 175°C/m during this period. After the surface convective zone appeared, the thickness of the surface convective zone was determined by the conductivity scan. It was found that the surface convective zone was 1cm initially and grew to 2cm in an-
Figure 5.4: The time development of temperature profiles during the first heating/cooling cycling. The envelope of the curves shows that the surface temperature cycling penetration decays exponentially in depth. There is not any surface mixing detected during this cycle. These profiles are taken by temperature scan and the origins of deviations on slopes have not been identified.
Figure 5.5: The time development of temperature profiles during the second heating/cooling cycling. The surface convection was detected by temperature scan at $t = 38hr$; see line e. A short dashed line in this graph presents the temperature profile taken 0.5hr before the surface zone was created. The maximum temperature gradient during that period was found to be $175^\circ C/m$. 
other 9 hours. A set of salinity sample was taken 8 hours after the surface convection was observed. The samples were weighed and the salinity profile was plotted with the temperature profile taken at same time, as shown in Figure 5.6. An isosaline layer with the thickness about 2cm in this figure represents the existence of a surface convective zone and confirms the results from the temperature and conductivity scans.

To detect the oscillatory nature of the instability, the detailed temperature fluctuation in the gradient zone below the surface was measured using a rank of fixed thermocouples before surface convection occurred. The temperature fluctuation at 1cm below the surface is presented in Figure 5.7. In Figure 5.7 (a), the data was taken at \( t = 37hr \) which was 1hr before the surface mixing was observed. In this curve the average peak to peak amplitude of the fluctuation was found to be 0.03°C which was in the order of the instrument (HP 177 Voltmeter) noise level. The amplitude of temperature fluctuation increased significantly at \( t = 37.3hr \); see Figure 5.7 (b), and reached the maximum fluctuation amplitude in the order of 0.2°C which presented a signal of the approach to surface mixing. In another 0.5hr, the surface convective zone was detected by the temperature and salinity scan.

A summary of significant observations during the surface heating/cooling cycling is given in Table 5.1. In this table, all times are counting from the beginning of the experiment.
Figure 5.6: Salinity and temperature profiles taken 8 hours after the surface convective zone created. An isosaline layer and an isothermal layer in this figure represent the existence of a surface convective zone.
Figure 5.7: Temperature fluctuations observed 1cm below the surface before surface convection occurred. (a) Measurement was taken at \( t = 37 \text{hr} \) which was 1hr before the surface convective zone was created. The temperature fluctuation at that time was in the order of instrument noise level. (b) Measurement was taken at \( t = 37.3 \text{hr} \) which was more than a half hour before the surface convective zone created. The amplitude of the temperature fluctuation increased significantly and reached the maximum value of the order of 0.2°C. This increase is an indication of approach toward surface convection.
Table 5.1: Summary of significant observations during the surface temperature cycling. All times in this table are counted from the beginning of the experiment.

<table>
<thead>
<tr>
<th>Cycle#1</th>
<th>Time(hr)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.5</td>
<td>Surface temperature reached the maximum $T_s</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>Surface temperature gradient reached the maximum $G_T</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Surface temperature reached the minimum $T_s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycle#2</th>
<th>Time(hr)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>31</td>
<td>Surface temperature reached the maximum $T_s</td>
</tr>
<tr>
<td></td>
<td>37.3</td>
<td>Increasing of temperature fluctuation at 1cm below surface was observed.</td>
</tr>
<tr>
<td></td>
<td>37.5</td>
<td>Surface temperature gradient reached the maximum $G_T</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>Surface convection zone of 1cm was detected by temperature and salinity scan.</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>Surface temperature reached the minimum $T_s</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>Surface convective zone grew to 2cm.</td>
</tr>
</tbody>
</table>
5.3.3 Characteristics of Creation Process

The general observations from Section 5.3.2 present solid evidence that the temperature cycling on surface can produce a surface convective zone under certain conditions. Further studies on the characteristics of surface zone generation process are discussed as follows.

(1) Detailed observations of surface zone appearance and evolution.

The temperature profiles taken successively after the surface convective zone was created are presented in Figure 5.8. The dashed curve in this graph shows a smooth temperature distribution near the surface half hour before the convective zone was detected. The position of boundary is very difficult to determine from this graph because of large temperature fluctuations at the boundary. However, it is still can be seen that the surface mixing with $1cm$ thickness occurred suddenly within $0.5hr$ and then grew in thickness gradually. The positions of the surface convective-gradient boundary were then determined by the conductivity profiles. The results are plotted as a function of time, as shown in Figure 5.9, which is consistent with the observations from temperature profiles.

The characteristic of sudden appearance of a surface convective zone with $1cm$ thickness is not surprising because the surface zone generation in our experiment is a purely thermal driven process in which the viscous drag sets a certain thickness margin criterion [3]. During the cooling period, the density on top may be higher than below and the surface fluid layer is then subject to the instability. This process may be analogous to the internal instability of
Figure 5.8: The temperature profiles taken successively after the surface convective zone was created. The surface convective zone was created suddenly and then grew in thickness gradually. The dashed line in this figure presents the temperature distribution half hour before the surface convective zone was created and shows a smooth gradient with a value of 175°C/m near the surface.
Figure 5.9: The positions of surface convective-gradient boundary determined by the conductivity profiles. The result from this figure is consistent with the result from Figure 5.8 showing the sudden creation and gradual growth of surface convective zone driven by surface temperature cycling.
a gradient zone heated from below, as we discussed in Chapter III, although in this case cooling is acting on the free water surface directly. Therefore the sudden appearance of a surface convective zone with 1cm thickness can be considered as the result of the gradient instability.

Further cooling on surface increases the surface convective circulation and pushes the surface convective-gradient boundary continuously downward. The thickness of the surface convective zone increases from 1cm to 2cm in 9 hours. It is noted that after the surface cooling cycle stopped, the surface convective-gradient boundary tended to move upward and recover itself. The boundary movement by surface temperature cycling will be discussed in next section.

(2) Oscillatory nature of the onset of surface mixing.

As described in Section 5.3.2, the increasing in amplitude of temperature oscillation 1cm below the water surface was observed just before the surface mixing. This observation reveals the oscillatory nature of the onset of surface convection resulting from the surface temperature cycling. Since the maximum temperature oscillation is in the order of 0.2°C and the temperature gradient near the surface at that time is 175°C/m, the maximum bulk fluid oscillation associated with the temperature oscillation is 1.2mm.

This fluid oscillatory motion at the onset of surface mixing is very similar to that occurring at the onset of internal gradient instability in which the maximum amplitude of bulk fluid oscillation is in the order of 2mm. It is interesting to note that even though the maximum temperature oscilla-
tion observed in the surface generation process is twice larger than that we found previously in the internal instability process, the maximum position displacement does not increase because of the large temperature gradient.

Another comparison that can be made between these two oscillation motions is the oscillation frequency. The characteristic frequency of the temperature fluctuation at the onset of surface mixing is determined by the means of Fourier transform. The frequency spectrum of the fluctuation, presented in Figure 5.10, gives the characteristic period in the order of 200sec which is almost twice longer than that in the internal process and far away from the theoretical predictions for the double-diffusive instability, perhaps because of the different boundary conditions.

(3) Prediction of surface convection.

As a thermal driven process, the generation of a surface convective zone can be predicted using the local stability margin calculation that is analogous to the prediction of internal instability of the gradient. The stability calculations were only made during the cooling period at each half hour interval and not applied to the heating period since the temperature gradient became negative during that time. The stability calculations were also made only for the region near the surface because the maximum temperature gradient always occurred at surface; see Section 5.1.2.

The local stability margin numbers calculated for the top 2cm are plotted in Figure 5.11 and Figure 5.12 as a function of time for the first cooling period and for the second cooling period respectively. The calculation uncertainty
Figure 5.10: The frequency spectrum of the temperature fluctuation at the onset of surface mixing. The characteristic period determined from this figure is in the order of 200 sec.
Figure 5.11: The local stability margin numbers calculated for the top 2cm near the surface during the first cooling period. The local stability margin numbers are plotted as a function of time and the minimum safety number in this period is 2.
Figure 5.12: The local stability margin numbers calculated for the top 2cm near the surface during the second cooling period. The minimum safety number in this period is 1.2 which predicts the onset of surface mixing. Half hour later, the surface convection was detected. The arrow in this figure indicates the time at which increasing in amplitude of temperature variation was observed.
on safety margin numbers is estimated to be ±0.4 and plotted as error bars in these figures.

During the first heating/cooling cycling, the minimum safety number of 2.0 was found when the temperature gradient reached the maximum value of 160°C/m; see Figure 5.11. As with the internal instability analysis within the gradient zone, the safety number of 2 implied that the gradient near the surface was still in the stable side. Since there was not any evidence showing the surface convection during this period, the prediction was consistent with the observations.

During the second cooling period, the safety number was dropped from 7.5 to 1.2 in two hours; see Figure 5.12. The minimum safety number of 1.2 was very close to the local gradient stability margin. This result predicted the onset of surface convection. Half hour later, the surface convective layer of 1cm was observed from the temperature and conductivity scans.

The agreement between the observations and the predictions made by stability margin calculations reveals the inherent relation between the internal gradient breakdown and the thermal driven process of surface convection. Therefore, it can be postulated that the onset of the thermal driven surface convection is the same process as the internal gradient instability with different boundary conditions. In both cases, the instability is caused by the locally increased temperature gradient which overcomes the stabilizing salinity gradient and produces a gradient overturn. Since the stability margin calculation is based on the local temperature and salinity gradients and the
local properties, the stability prediction should be valid in both cases. However, the boundary conditions between these two cases are so different that the oscillation frequencies could not be compared with each other.

(4) Growth of the surface convective zone.

In the previous discussion, we know that after the surface convective zone created, it grew gradually and reached the maximum thickness of 2 cm in 9 hours. Although the surface convective zone was very thin and many effects may be involved in the boundary behavior, Nielsen's boundary equilibrium correlation still can be applied to assist understanding some aspect of the growing processes.

It was found that the salinity gradient near the surface convective-gradient boundary changed very slightly, from 16%/m to 20%/m in 9 hours after the surface convective zone was created, although the thickness of the convective zone increased from 1 cm to 2 cm. Meanwhile, the temperature gradient near the surface convective-gradient boundary decreased with time and the temperature of the surface convective zone also decreased continuously due to the surface cooling. It was found that as the result of surface heating/cooling cycling the temperature gradient decreased from 230°C/m to 100°C/m in 9 hours when the surface convective zone grew.

The correlation of the temperature gradient and the salinity gradient near the surface convective-gradient boundary is presented in Figure 5.13. The solid line in this figure is Nielsen's boundary criterion and the measured values at different time are shown as markers with labels on them. It is
Figure 5.13: The correlation of temperature gradient and salinity gradient near the surface convective-gradient boundary at different times after the surface convective zone was created. In this figure the gradient correlation was approaching to Nielsen's boundary equilibrium criterion when the surface convective zone grew.
shown in this figure that the gradient correlation approaches to Nielsen's boundary equilibrium criterion as the surface convective zone grows. This result represents the progress of the surface convective-gradient boundary achieving to the equilibrium.

5.4 Movements of Surface Convective-Gradient Zone Boundary by Surface Temperature Cycling

5.4.1 Observations of Boundary Movement by Surface Temperature Cycling

It has been described in Section 5.3 that after the surface zone was created, the surface convective-gradient boundary moved downward during the cooling period to approach the equilibrium and tended to move upward during the heating cycle. This boundary movement due to the surface heating/cooling cycling is presumably not the same process as the surface convective generation. In order to investigate the characteristics of the boundary movement by surface temperature cycling, another experiment run in which a stationary surface convective zone persisted initially was conducted.

In this experiment, the surface convective zone with 12cm thickness was pre-created by gradient modification and maintained by a slow surface wash. The artificial mixing process seems to be not reversible, and the surface convective zone had persisted and reached the equilibrium for a long time. The initial temperature and salinity profiles taken at the beginning of heat-
The heating/cooling cycling was then applied on the surface using the same procedure as we described before. The temperature cycling persisted for seven days with approximately one day cycling period. The temperature cycling had been interrupted two times, in which the heating or cooling was stopped for couple hours. Since these interruptions only changed the period of heating/cooling cycling slightly, it could not make any significant effect on our investigations.

The maximum peak to peak temperature variation at the top of surface convective zone during one day period was observed to be from 5°C to 10°C, and the corresponding temperature variation near the surface convective-gradient boundary was observed to be from 3°C to 6°C. The decreasing amplitude of temperature variation with depth is a characteristic of heat wave propagation but the situation here is complicated by the convection that occurs during parts of the heating/cooling cycle (See 5.4.2). The maximum temperature variations near the boundary during each period are plotted in Figure 5.15 (a) as a function of time.

It was found that there was a surface convective-gradient boundary movement associated with the temperature variations at the boundary. To investigate the relation of temperature variation and boundary movement, the maximum boundary movements during each period are also plotted in Figure 5.15 (a) as a function of time along with the temperature variations. In this plot, the positions of the boundary were determined from conductivity
Figure 5.14: The initial temperature and salinity profiles taken at the beginning of heating/cooling cycling in the boundary movement experiment.
Figure 5.15: (a) Maximum temperature variations at the surface convective-gradient boundary during each surface heating/cooling cycling are plotted as a function of time. The maximum boundary movements associated with the temperature variation at the boundary show the same oscillation characteristic as the temperature variation. (b) The average boundary position was continuously moving downward during surface temperature cycling and recovered to its original position in 4 days. In this figure, the positions of the boundary were determined from conductivity profiles.
profiles.

It can be seen from Figure 5.15 that the heating/cooling on surface produced a daily position oscillation on the surface convective-gradient boundary in the order of 1 cm. This position oscillation was in phase with the temperature cycling; it moved upward during the heating period and moved downward during the cooling period. However, the average boundary position moved downward continuously from 92 cm to 90 cm during the seven days of surface temperature cycling.

The process of the boundary recovering to its original position was also observed in our experiment; see Figure 5.15 (b). After the surface heating/cooling cycling stopped, the average boundary position was moving up gradually and back to the original equilibrium position in 4 days.

5.4.2 Characteristics of Boundary Movement by Surface Temperature Cycling

As discussed in Section 5.1, the surface temperature cycling produces a non-steady thermal convection which is more erosive than the steady thermal convection. It has been observed that the heat transfer by surface heating and by surface cooling are two distinct processes. During the heating period, the temperature increases on the top of surface zone very rapidly and produces a negative temperature gradient downward, while the salinity maintains a uniform in the convective zone. Therefore, during the heating period, the heat transfer is dominated by heat conduction which transfers
the heat from the surface into the surface convective zone. In contrast, the heat transfer during the cooling period is dominated by natural convection since the decreasing of temperature on the top of surface zone produces a buoyancy force which drives cold fluid downward and transfers the heat out of the surface convective zone.

One characteristic of the effect of surface temperature cycling on the movement of the surface convective-gradient boundary is the coherence of the temperature variation near the boundary and the position movement of the boundary, as seen in Figure 5.15. This result can be explained as the two different heat transfer patterns of heating/cooling cycling play different roles on boundary movement. The surface cooling increases surface zone convection, enhances the boundary erosion and pushes the boundary position downward, whereas the surface heating produces a heat conduction in the surface zone and the boundary position moves upward due to the diffusion of salt. The combined effect of heating/cooling cycling will move the boundary up and down, and produce a boundary position oscillation.

It has been found that during the surface temperature cycling, the salinity gradient near the boundary did not change very much but the temperature gradient near the boundary varied significantly. The correlation of temperature and salinity gradients near the boundary is plotted in Figure 5.16 in which the solid line is the Nielsen’s boundary equilibrium criterion. In this figure, the temperature and salinity gradient data were taken immediately after each heating cycle and cooling cycle. It is shown from Figure 5.17 that
Figure 5.16: The correlation of temperature and salinity gradient near the surface convective-gradient boundary in the boundary movement experiment. The correlation was far away from equilibrium after the cooling cycle and approached to the equilibrium after the heating cycle. The average correlation represents the net effect of surface temperature cycling which pushes the surface convective-gradient boundary downward.
gradient correlations are far away from the equilibrium after the cooling cycle while they approach the equilibrium after the heating cycle. The oscillation in gradient correlation corresponds to the oscillation in boundary position which was observed.

It is noted in Figure 5.16 that although the gradient correlation is varying during the heating/cooling cycling, the average gradient correlation is still below the equilibrium. This result represents that the average surface convective-gradient boundary position is in the progress of moving downward, and reveals the unbalanced effects of surface heating and surface cooling on the movement of boundary position which confirms the nonlinearity in the relation between heat transfer and erosion first noted from Nielsen's study [3].

5.5 Summary and Discussion

In order to investigate the behaviors and characteristics on the creation and growth of the surface convective zone produced by surface temperature cycling, two experiment runs were conducted in our laboratory tank. The experiment conditions were examined carefully and the effects of wind mixing, evaporation and salt diffusion can be neglected.

In the first experiment run, a sudden appearance of a surface convective zone with 1cm thickness was observed after two complete heating and cooling cycles. The increasing amplitude of temperature oscillation was detected at the onset of surface mixing. The generation of surface convective zone
was predicted using the local stability margin calculation that is analogous to the prediction of internal instability of the gradient. During the second cooling period, a minimum safety number of 1.2 was found near the water surface and the surface convective zone was observed half hour later. Based on these experiment observations, it can be postulated that the onset of the thermal driven surface convection is the same process as the internal gradient instability but with different boundary conditions.

In the second experiment run, it was found that surface convective-gradient boundary movement was associated with surface temperature cycling. The boundary movement was in phase with the temperature variation at the boundary, and boundary moved upward during the heating period and moved downward during the cooling period. The net effect of surface temperature cycling will enhance the boundary erosion and push the average boundary position downward. This experiment observations agree with Nielsen’s prediction that the surface heating/cooling cycling produces a non-steady thermal convection which is more erosive than steady thermal convection associated with the same average heat transfer rate because of a nonlinearity in the relation between heat transfer and erosion.
References


CHAPTER VI
Conclusions

6.1 Summary of Experimental Conditions

The dynamic processes which involve internal gradient stability, boundary behavior between gradient zone and convective zone, and surface zone creation and growth by surface temperature cycling were studied experimentally in a laboratory tank. The salinity distribution and temperature distribution in the tank were so established as to provide conditions which were similar to those in a solar pond. The electrical sidewall heat loss control device eliminated the lateral heat flux and made a one dimensional simulation possible. Both temperature and salinity in the tank were well controlled to meet the experiment requirement by properly designed heating-cooling system and injection and surface wash devices. Thermocouples were used as the temperature sensors for all the temperature measurements in our experiments, and a conductivity probe was developed to obtain an instantaneous salinity profile accompanied with the temperature measurement simultaneously. The sensors were carefully calibrated and the corrections of data for sensor time constant were considered.
6.2 Important Observations and Results

Under these experiment conditions, three experiments concerning internal instability, gradient-convective boundary behavior, and surface zone creation and growth by surface temperature cycling respectively were conducted to improve our understanding of these dynamic processes which play important roles in the performance of solar ponds. The major observations and conclusions obtained from these laboratory studies are summarized as follows.

1. Prediction and observation of internal instability in gradient zone.

   (a) The stability analysis method developed in Section 3.2 using the concept of local stability margin and the result of linear stability analysis is practically useful for evaluating internal stability within the gradient zone with nonlinear temperature and salinity gradients. This internal local stability evaluation method has been used throughout all our experiment and the predictions of the occurrence of gradient instability have been made successfully.

   (b) The fluid instability in the gradient zone occurred at the minimum salinity gradient region and appeared as a convective layer a few centimeters in thickness initially. The minimum stability margin number of 1 was found as the condition for the onset of gradient instability, in agreement with theoretical prediction.

   (c) The onset of instability in the gradient zone occurs as the growth of very small amplitude oscillatory motions which is verified by the observations of temperature oscillations increasing in amplitude before the gradient break-
down. The maximum bulk fluid oscillation was estimated to be in the order of 2\(\text{m m}\) on the basis of the existing gradient and the observed maximum temperature oscillation of 0.12°C. The characteristic period of the oscillation was determined as 110sec, which is above the theoretical prediction that is 81sec. This discrepancy presumably results from the difference between the actual boundary condition and that assumed in the theory.

2. Structure of temperature and salinity fluctuation at gradient - convective boundary.

(a) There is a transition region with approximate 1.5cm thickness at the gradient-convective interface. Large temperature and salinity fluctuation \(\delta T \sim 0.5^\circ C\) and \(\delta S \sim 0.15\%\) were found with entirely different characteristics at the upper portion and at the lower portion of the transition region. An excellent coincidence exists between the temperature fluctuation and the salinity fluctuation, showing that the fluid motions involved in the boundary behavior are mass motions which can be either a convective flow or a bulk oscillation.

(b) The r.m.s. profiles of fluctuation amplitude were found to have a maximum within the transition region and decrease rapidly on either side of the interface. The position of the maximum r.m.s. temperature fluctuation extended closer to the convective zone past the position of the maximum r.m.s. salinity fluctuation by approximately 0.5cm. Also different fluctuation tendencies in the direction of peaks at the upper and lower portion of the transition region were represented by third order moment \(\overline{\delta^3}\) and \(\overline{\sigma^3}\) profiles.
(c) The fluctuation length scales were defined as $\theta/G_T$ and $\sigma/G_S$ to represent the effect of the fluctuation in space. In the transition region, the temperature fluctuation length scale was $\sim 3$ times larger than the salinity fluctuation length scale, whereas in the gradient zone these two length scales were compatible.

(d) The characteristic frequencies of the fluctuations at the upper and lower portion of the transition region were found to be $300\,\text{sec}$ and in the range from $120\,\text{sec}$ to $400\,\text{sec}$ respectively. The range of characteristic fluctuation frequencies at the lower portion of the transition region agree surprisingly well with the results calculated from a boundary layer model which are in the range from $112\,\text{sec}$ to $400\,\text{sec}$.

(e) Oscillatory behavior at the upper portion of the transition region and the diffusive boundary layer character of the lower portion of the transition region were studied by the simultaneous measurements of temperature fluctuation at different positions within the gradient-convective interface. It is suggested that there are two distinct dynamic processes involved in the boundary behavior. One is the boundary layer process at the lower portion of the transition region and another is the bulk fluid oscillation at the upper portion of the transition region adjacent to or in the gradient. The overlapping of these two processes constructs a core of the transition region at the center.

3. Effects of temperature cycling on surface zone creation and growth.

(a) The surface convective zone can be produced by the surface tempera-
ture cycling in some circumstances. The surface convective zone was formed suddenly with 1cm thickness and then grew slowly to approach Nielsen's stationary boundary criterion.

(b) The surface convective zone produced by surface temperature cycling was initiated as the increasing in amplitude of bulk fluid oscillation near the surface. Oscillation was indicated by the measurements of temperature oscillations. In our conditions, the oscillation period is in the order of 200 – 300 sec, which is far away from the predicted value calculated by using double-diffusive stability theory in which a free-free boundary condition is assumed.

(c) The local stability margin calculations were applied to predict the onset of surface convection. The minimum safety number of 1.2 was found near the surface half an hour before the surface convective zone was observed. By combining this result with the oscillatory nature of surface instability, it can be postulated that the creation of a surface convective zone produced by surface temperature cycling is the same process as the internal gradient instability but with different boundary conditions.

(d) The surface temperature cycling also produces surface convective-gradient boundary movement, given an existing surface zone. The boundary movement was found in phase with the surface zone temperature variation, and the net effect of surface temperature cycling was to enhance the boundary erosion and push the average boundary position downward. This result provides evidence that a non-steady thermal convection is more erosive than steady thermal convection associated with the same average heat transfer.
rate and there is a nonlinear relation between heat transfer and erosion.

All these experimental results from our laboratory studies present a rich variety of dynamic processes associated with the internal gradient instability, gradient-convective zone boundary behaviors and surface convective zone creation and growth. These results also reveal some inherent relations between each other. A similarity between the creation of surface convective zone by surface temperature cycling and the internal gradient breakdown by steady heating from below has been found as the result of double-diffusive instability. Although the surface convective zone growth can be considered as a boundary process, non-steady heat transfer by surface temperature cycling produces a nonlinear effect on the boundary movement.

6.3 Applications to Solar Pond Operations

Since all the processes we investigated in our laboratory experiments can be considered as scale-independent issues, those observations and results discussed above may be directly applied to large scale solar ponds. On the other hand, as examples of double-diffusive convection, our experimental results may also supply some information to improve the understanding on the similar processes that occur in oceanography, astrophysics, geology, geophysics, metallurgy and materials science, but discussion of these is out of our scope of present studies. Some possible application to solar pond operations are described as follows.

(1) More evidences have been provided from the laboratory experiments
to prove the usefulness of the stability margin calculations introduced in Section 3.2. Using the concept of double-diffusive instability and localized stability margin, an easy and practically useful field evaluation of operational NaCl solar pond internal stability can be performed by application of the straightforward calculational procedure discussed above in Section 3.2. It is noted that since the actual stability can be influenced by factors such as wall-induced effects and irregular heat sources, the stability margin should be maintained larger than two everywhere in the pond to ensure stable pond operation. Since we know the instability always first occur at the position with the minimum salinity gradient, more attention should be paid at that region.

(2) It has been shown from experiment that the surface zone can be generated by surface temperature cycling alone when other effects are excluded. This result implies that a surface convective zone may be created in operating solar pond even if the whole pond is built in a greenhouse or completely covered. Also we know that a non-steady thermal convection is more erosive than steady thermal convection with the same average heat flow. Therefore, in order to keep a relative thinner surface zone in operating pond, we not only need to eliminate the effects of wind and evaporation, but also need to maintain a higher salinity gradient near the surface boundary to reduce the boundary movement produced by surface temperature cycling.

(3) Although a full understanding of the dynamic processes associated with zone boundary behaviors is not yet available, a basic physical picture
has been revealed from the laboratory observations. It has been found that two distinct processes, boundary layer process and bulk fluid oscillation, may play important roles on the gradient zone erosion. This result may provide a guideline for boundary movement control if any preventive or corrective measurements may be taken.

6.4 Recommendations for Further Studies

Despite the fact that many aspects of these processes have been studied in our laboratory experiment intensively, there are still many important questions that remain to be answered. Further studies in laboratory tanks which immediately related with the dynamic processes discussed above are recommended as follows.

(1) The structure of the temperature and salinity fluctuation at gradient-convective boundary investigated above is only one dimensional and provides no information about the wave length of the oscillation near the gradient zone as well as the size and the horizontal movement of the convection cells in the convective region. The different direction tendency of temperature fluctuations observed at the upper portion and at the lower portion of transition region produces a peak in the instantaneous temperature profile within the transition region. The discontinuity of temperature gradient at the peak reveals a possible existence of a local lateral convective flow. These problems may be solved by a two dimensional study in which both vertical and horizontal structures of temperature and salinity fluctuations can be obtained.
(2) It was found that after the surface convective zone was created by surface temperature cycling, the surface convective-gradient boundary was moving downward gradually. When the surface temperature cycling stopped, the boundary was moving upward. Although the difference between growing rate and recovering rate has been found qualitatively, more detailed studies on the growing and recovering rate of surface convective zone as the result of surface temperature cycling are needed to further understand the nonlinearity in the relation between heat transfer and erosion.

(3) Since all the dynamic processes discussed above have been identified as mass motions, it is possible to apply some fluid visualization methods such as dye markers, thymol blue, shadowgraphs, interferometer or others to visually study the top view and side view pattern of the fluid motions. Combined with the temperature and salinity measurements, a more complete physical picture may be obtained.
APPENDIX A

Electrical Diagram and Computer Program of
Sidewall Temperature Control

A.1 Electrical Diagram

There are six groups of heaters and 16 heaters in each group on the guard
cylinder. The positions of these heaters on the guard cylinder are shown in
Figure 2.1. Some of the resistors are 225 $\Omega$ and some are 10 $\Omega$. The 225 $\Omega$
groups are connected in parallel and the 10 $\Omega$ groups are connected in series-
parallel so that the resistance of each group is of the order of ten ohms, as is
convenient for power supplies used.

A diagram showing the electrical circuit for the control of these heaters
is given in Figure A.1. In this circuit the operating voltage for relays,
$L_1,\ldots, L_6$, is 6 V which is supplied by a transformer $T$. $A_1,\ldots, A_6$, are
channels of the actuator in HP 3974 A data acquisition/control unit in which
$A_C$ is the common line of those channels. The computer monitors the tem­
perature differences between the plastic tank and the guard cylinder at six
different levels. If the temperature difference at a certain level is greater than
Figure A.1: The circuit for the resistors on and off control.

—0.4°C, the computer will send a command to data acquisition/control unit. Then the channel of actuator for that level will act and the heaters at that level will be on. If the temperature difference is smaller than —0.2°C, the actuator will be opened to stop heating.
A.2 Computer Program

The computer programs for sidewall temperature difference monitoring and for heaters on and off control are shown as follows.

```
10 ! TEMPERATURE CONTROL
20 DIM A(6)
30 DEF FNT(X)=25775.2*X+590800*X^2
40 FN END
50 CLEAR 709! RESET ACTUATOR
60 BEEP 50,100
70 OUTPUT 709; "TD"
80 ENTER 709 ; D$
90 DISP D$
100 OUTPUT 709 ; "VR1VT1VD5VA1AI0"
110 ENTER 709 ; A(0)
120 IF FNT(A(0))>=-.2 THEN OUTPUT 709 ; "DO3,0"
130 IF FNT(A(0))<=-.4 THEN OUTPUT 709 ; "DC3,0"
140 WAIT 2000
150 OUTPUT 709 ; "VR1VT1VD5VA1AI1"
160 ENTER 709 ; A(1)
170 IF FNT(A(1))>=-.2 THEN OUTPUT 709 ; "DO3,1"
180 IF FNT(A(1))<=-.4 THEN OUTPUT 709 ; "DC3,1"
190 WAIT 2000
200 OUTPUT 709 ; "VR1VT1VD5VA1AI2"
210 ENTER 709 ; A(2)
220 IF FNT(A(2))>=-.2 THEN OUTPUT 709 ; "DO3,2"
230 IF FNT(A(2))<=-.4 THEN OUTPUT 709 ; "DC3,2"
240 WAIT 2000
250 OUTPUT 709 ; "VR1VT1VD5VA1AI3"
260 ENTER 709 ; A(3)
270 IF FNT(A(3))>=-.2 THEN OUTPUT 709 ; "DO3,3"
280 IF FNT(A(3))<=-.4 THEN OUTPUT 709 ; "DC3,3"
290 WAIT 2000
300 OUTPUT 709 ; "VR1VT1VD5VA1AI4"
310 ENTER 709 ; A(4)
```
320 IF FNT(A(4)) > -.2 THEN OUTPUT 709 ; "DO3,4"
330 IF FNT(A(4)) < -.4 THEN OUTPUT 709 ; "DC3,4"
340 WAIT 2000
350 OUTPUT 709 ; "VR1VT1VD5VA1A15"
360 ENTER 709 ; A(5)
370 IF FNT(A(5)) > -.2 THEN OUTPUT 709 ; "DO3,5"
380 IF FNT(A(5)) < -.4 THEN OUTPUT 709 ; "DC3,5"
390 WAIT 2000
400 GOTO 40
410 END
APPENDIX B

Salinity Gradient Modifications

The salinity gradient can be modified by appropriate rapid injection of brine in the desired region. The modification procedures are described as follows.

(1) Determination of injection rate. It is necessary to control the injection flow rate carefully to obtain a mixing only at the diffuser level. It was found from laboratory test [1] and observations at El Paso solar pond [2] during the gradient formations that if injection Froude number is around 16 to 18, the injected fluid mixes only with the fluid at the diffuser level. The Froude number is defined as

\[ F_r = \sqrt{\rho_o v_j^2 / (gh_j \rho_o - \rho_j)}, \]  

where \( \rho_o \) is the density of ambient fluid, \( \rho_j \) is the density of injected fluid, \( v_j \) is the injection velocity at the diffuser outlet, \( g \) is the acceleration of gravity, and \( h_j \) is the gap width of the diffuser. If we chose \( F_r = 17 \), the injection velocity can be determined by

\[ v_j = 17 \sqrt{(gh_j \rho_o - \rho_j) / \rho_o}. \]
For given diffuser, therefore, the injection rate is

\[ Q_j = 2\pi r_j h_j v_j, \]  

(B.3)

where \( Q_j \) is the injection flow rate, \( r_j \) is the radius of the diffuser.

(2) Determination of injection time at certain level. Using the injection rate we calculated above, if a very thin jet of salinity \( S_j \) is discharged at height \( z \) where the ambient salinity is originally \( S_0 \), it fully mixes with the ambient fluid within a thin region \( \Delta z \) centered on height \( z \). After some time \( t \) the volume of this layer has expanded from \( V_o = A\Delta z \) to \( V_o + Q_j t \), and the local salinity has changed to

\[ S = \frac{S_0 \rho_o V_o + S_j \rho_j Q_j t}{\bar{\rho} (V_o + Q_j t)}, \]  

(B.4)

where \( \bar{\rho} = (\rho_o V_o + \rho_j Q_j t)/(V_o + Q_j t) \). Therefore, in order to obtain a desired salinity \( S \) at certain level, the injection time at that level should be

\[ t = \frac{\rho_o V_o (S - S_o)}{\rho_j Q_j (S_j - S)}. \]  

(B.5)

In this expression, \( V_o = A\Delta z \), where \( A \) is the area of the pond at height \( z \) and \( \Delta z \) is the vertical thickness centered on \( z \) at which the mixing occurred.

(3) Determination of mixing thickness \( \Delta z \). It is not easy to determine the mixing thickness \( \Delta z \) from the calculation since so many effects are involved in the injection process. However, the mixing thickness can be rather simply determined by making a test injection. Because after a certain injection time \( t \), both the original salinity \( S_o \), the injected salinity \( S_j \), and mixed salinity \( S \) can be measured, the \( V_o \) and therefore \( \Delta z \) can be solved by inserting \( t \),
$Q_j$, $S_o$, $S_j$, $S$ as well as $\rho_o$ and $\rho_j$ which can be determined from $S_o$ and $S_j$ respectively, into Equation B.5. This experimentally determined $\Delta z$ then can be used as standard space interval in the gradient modification.

(4) Gradient modification by scan. Above discussions show that the net result of injection is that the salinity within certain thickness $\Delta z$ centered at height $z$ will change. If the desired salinity profile is known, the salinity gradient can be modified by moving the diffuser up or down in discrete steps, each of size $\Delta z$, through the region we desired, and keeping the diffuser at each position for the predetermined time $t$. This procedure may be repeated until the satisfactory of salinity gradient is achieved.

More information concerning the gradient modification also can be obtained from references [3] [4] [5].
References


APPENDIX C

Conversion of Specific Gravity to Salinity in Percent by Weight

C.1 Definition

The definitions of specific gravity are

\[ S.G.(\frac{20^\circ C}{4^\circ C}) = \frac{\text{mass of solution at } 20^\circ C}{\text{mass of same volume of pure water at } 4^\circ C} \]

or

\[ S.G.(\frac{20^\circ C}{20^\circ C}) = \frac{\text{mass of solution at } 20^\circ C}{\text{mass of same volume of pure water at } 20^\circ C} \]

\[ S.G.(\frac{T}{T}) = \frac{\text{mass of solution at } T}{\text{mass of same volume of pure water at } T} \]

where \( T \) is the temperature under which the sample is weighed, usually the room temperature.

Since the definition of density is

\[ \text{Density}(T) = \frac{\text{mass of solution}}{\text{volume of solution at temperature } T} \]

the definitions of specific gravity also can be written as

\[ S.G.(\frac{20^\circ C}{4^\circ C}) = \frac{\text{density of solution at } 20^\circ C}{\text{density of pure water at } 4^\circ C} = \frac{D(20^\circ C)}{D_w(4^\circ C)} \]
or

\[ S.G.(\frac{20°C}{20°C}) = \frac{\text{density of solution at } 20°C}{\text{density of same volume of pure water at } 20°C} = \frac{D(20°C)}{D_w(20°C)}, \]

\[ S.G.(\frac{T}{T}) = \frac{\text{density of solution at temperature } T}{\text{density of same volume of pure water at same } T} = \frac{D(T)}{D_w(T)}. \]

### C.2 Relation of Salinity and Density

\[ S = \frac{C_1}{2C_2} \left( \sqrt{1 + \frac{4C_2D_w(T)}{C_1^2} \left( \frac{D(T)}{D_w(T)} - 1 \right) - 1} \right) \quad \text{(C.1)} \]

where,

\[ D_w(T) = \sum_{i=0}^{4} A_i T^i \]

\[ C_1 = \sum_{i=0}^{4} A'_i T^i \]

\[ C_2 = \sum_{i=0}^{4} A''_i T^i \]

\( S \) is salinity in salt percent by weight, \( T \) is temperature, \( D(T) \) is density of solution at temperature \( T \) in \((kg/m^3)\), and \( D_w(T) \) is density of pure water at same temperature in \((kg/m^3)\). \( C_1 \) and \( C_2 \) are compensation factors, and \( A_i \), \( A'_i \) and \( A''_i \) are calculation coefficients for \( D_w \), \( C_1 \) and \( C_2 \) respectively. The values of \( A_i \), \( A'_i \) and \( A''_i \) are given in Table C.1. The data are obtained from *Saline Water Conversion Engineering Data Book*, Second Edition, Office of Saline Water, United States Department of the Interior (1971), and fitted by the least-square curve fitting routine. The discrepancy between the calculated \( S \) and the value obtained from the table at most 1.5 % at the highest values of temperature and salinity.
Table C.1: The values of $A_i$, $A'_i$ and $A''_i$.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_i$</td>
<td>1</td>
<td>$4.57 \times 10^{-5}$</td>
<td>$-8.283 \times 10^{-6}$</td>
<td>$6.412 \times 10^{-8}$</td>
<td>$-2.911 \times 10^{-10}$</td>
</tr>
<tr>
<td>$A'_i$</td>
<td>$7.92 \times 10^{-3}$</td>
<td>$-6.889 \times 10^{-5}$</td>
<td>$1.359 \times 10^{-8}$</td>
<td>$-1.604 \times 10^{-8}$</td>
<td>$8.263 \times 10^{-11}$</td>
</tr>
<tr>
<td>$A''_i$</td>
<td>$-1.474 \times 10^{-5}$</td>
<td>$3.502 \times 10^{-6}$</td>
<td>$-9.429 \times 10^{-8}$</td>
<td>$1.195 \times 10^{-9}$</td>
<td>$-5.658 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

C.3 Conversion Formulas of $S.G.$ to $S(\%)$

1. For $S.G.(T/T)$

Since $S.G.(\frac{T}{T}) = D(T)/D_w(T)$, from Equation C.1 the conversion formula of $S.G.(\frac{T}{T})$ to $S(\%)$ can be written as

$$S = \frac{C_1}{2C_2} \left( \sqrt{1 + \frac{4C_2D_w(T)}{C_1^2}(S.G.(\frac{T}{T}) - 1)} - 1 \right). \tag{C.2}$$

All definitions here are as same as in Equation C.1.

2. For $S.G.(20^\circ C/4^\circ C)$

$$S = 132.8 \left( \sqrt{1 + 2.156(S.G.(\frac{20^\circ C}{4^\circ C})/0.9982 - 1)} - 1 \right). \tag{C.3}$$

3. For $S.G.(20^\circ C/20^\circ C)$

$$S = 132.8 \left( \sqrt{1 + 2.156(S.G.(\frac{20^\circ C}{20^\circ C}) - 1)} - 1 \right). \tag{C.4}$$

The plot of the relation of $S.G.(20^\circ C/20^\circ C)$ and salinity in $\%$ by weight is shown in Figure C.1. This plot relates $S.G.$ and salinity to within a small fraction of a percent.
Figure C.1: Estimation of Salinity, % by weight beginning with the Specific gravity \( S.G.(20^\circ C/20^\circ C) \) rather than at \( S.G.(20^\circ C/4^\circ C) \). Specific gravity at around \( 20^\circ C/20^\circ C \) is the quantity most often measured from weighing samples collected from throughout the vertical column of a salinity gradient solar pond.
Figure D.1: The circuit of the conductivity measurement. $P$ is the four wire conductivity measurement probe.

**Input**

$I_S$: Lock-in Amplifier Internal Signal Output. $f = 1000\text{Hz}$.

$R$: 10$K\Omega$ Resistor.
Output

FT: Single Pass Filter Transformer. Impedance 5000Ω : 50000Ω.

LA: Lock-in Amplifier. Input sensitivity setting 2mV.

V: AC voltmeter. Range setting 2V.
APPENDIX E

Scan Driving Device and Electrical Diagram of Scan Control

Figure E.1: The sketch of the scan driving device. In this sketch, $M$ is the synchronous motor and $PL$ is the drum. $TR$ is a threaded rod. $TB$ is a threaded block which travels along the threaded rod and makes limit switch $LS$ open or close. $G_1$ and $G_2$ are gears which can be changed to obtain different scan speed.
Figure E.2: Electrical diagram of scan control. $B$ is a power supply which gives 6 V output to operate the relays, $L_{11}$, $L_{12}$ and $L_{13}$. The computer sends commands to the channels of the actuator, $A_{11}$, $A_{12}$ and $A_{13}$, which controls the relays and makes the scan start, reverse and stop. $A_D$ is the common line of $A_{11}$, $A_{12}$ and $A_{13}$. The labels 1 and 4 on motor indicate the main motor coil, while the labels 2 and 3 are the starting coil.
APPENDIX F

Computer Program for Scan Control and Data Collection

10 ! TEMPERATURE AND SALINITY SCAN
20 OPTION BASE 0
30 CLEAR
40 CLEAR 709
50 DIM W1(200,1), W2(200,1) ! TEMPERATURE, CONDUCTIVITY
60 S1 = 2! SCAN INTERVAL (HOUR)
70 S3 = 104! TOP OF SCAN (CM)
80 S4 = 60! BOTTOM OF SCAN (CM)
90 S5 = 1! SCAN INCREMENT (CM)
100 B0 = 4926! SCAN SPEED (MS PER CM)
110 DEF FNT(X) = 25775.2*X+590800!*X^2
120 DEF FNS(X) = .6*X^(-.9)
130 FN END
140 ON TIMER# 1, S1*3600000! GOSUB 180
150 GOSUB 180
160 GOTO 160
170 END
180 ! RUN SCAN
190 CLEAR 709
200 OUTPUT 709 ; "TD"
210 ENTER 709 ; D$
220 WAIT 1000
230 OUTPUT 709 ; "DO3,12" ! SCAN DOWN
240 WAIT 100
250 OUTPUT 709 ; "DC3,13" ! CLOSE BY PASS
260 WAIT 100
270 N1 = (S3-S4) DIV S5
280 I3 = 0
290 I2 = 0
300 OUTPUT 709 ; "DC3,11" ! START MOTOR
310 DISP "SCAN DOWN"
320 BEEP
330 ON TIMER# 2, S5*B0 GOTO 340
340 OUTPUT 709 ; "VT1VD5VA1AI18" ! TEMPERATURE
350 ENTER 709 ; W1(ABS(I2),I3)
360 OUTPUT 709 ; "VT5VD5VA1AI19" ! CONDUCTIVITY
370 ENTER 709 ; W2(ABS(I2),I3)
380 BEEP 200,30
390 I2 = I2+1
400 IF I2<=N1 THEN GOTO 160
410 IF N1=0 THEN GOTO 570 ELSE GOTO 420
420 OFF TIMER# 2
430 OUTPUT 709 ; "DO3,11" ! STOP MOTOR
440 BEEP
450 WAIT 5000
460 OUTPUT 709 ; "DO3,13" ! OPEN BY PASS
470 WAIT 100
480 OUTPUT 709 ; "DC3,12" ! SWITCH DIRECTION UP
490 WAIT 100
500 I3 = 1
510 I2 = -N1
520 N1 = 0
530 OUTPUT 709 ; "DC3,11" ! START MOTOR
540 DISP "SCAN UP"
550 BEEP
560 GOTO 330
570 OFF TIMER# 1
580 WAIT 1000
590 OUTPUT 709 ; "DO3,11" ! STOP MOTOR
600 BEEP
610 ! PRINT DATA
620 PRINT
630 PRINT
640 PRINT
650 PRINT D$
660 PRINT
670 PRINT "Z(CM);TD(C);TU(C);SD(%);SU(%)"
680 I8 = 0
690 FOR I7=S3 TO S4 STEP -S5
700 PRINT USING 820 ; I7, FNT(W1(I8,0)), FNT(W1(I8,1)), FNS(W2(I8,0)), FNS(W2(I8,1))
710 I8 = I8+1
720 NEXT I7
730 PRINT
740 PRINT
750 IMAGE 3D.D, ":", DD.D, ":", DD.D, ":", DD.D, ":", DD.D
760 RETURN
LIST OF REFERENCES

Chapter I


Chapter II


Chapter III


15 A. Swift, Personal communication (1988).

16 A. Betbeze, Personal communication (1987).


Chapter IV


Chapter V


Appendix B


