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FLUID DYNAMICS OF DOUBLE DIFFUSIVE SYSTEMS

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2. ACCOMPLISHMENTS TO DATE

2.1 OVERVIEW

The major accomplishments of our initial research period (**August 1, 1987 to March 1, 1990**) are as follows; we

1. Completed construction of the experimental facility. Originally, it had been our intent to modify an existing facility in our laboratory. When this became impractical we constructed a new stand-alone facility. It is described in Section 2.2.1 and Appendix A.1.
2. Modified an existing three-dimensional numerical code developed in our laboratory, SEAFLOS1, by incorporating a salinity transport equation. The code is described in Section 2.2.2.
3. Developed experimental and analytical techniques, and performed both physical and numerical experiments for a wide range of initial and boundary conditions.
4. Focused our overall research effort to answer the following four questions pertaining to the formation of convective intrusions due to lateral temperature gradients established by sidewall heating.
 - (a). What is the internal structure of the convective intrusions as a function of the initial stratification and sidewall heating rates?
 - (b). What is the correct scaling for the initial vertical dimension of the intrusions?
 - (c). How does the merging process vary as a function of initial stratification and sidewall heating rate?
 - (d). Is the sidewall heating critical for continued propagation of the intrusions, or is it merely a trigger which releases the internal instability in the fluid?

These accomplishments are summarized below and presented in more detail in Appendices 1 and 2 (facilities and techniques) and Appendix 3 (research results).

2.2 FACILITIES

2.2.1 Experimental Facilities

The experimental facility consists of a 4.0m long, 0.8m wide and 0.5m deep tank as shown in Figure A.1.1. The walls are of composite construction, the inner pane being 6.25mm thick tempered float glass separated by a 6.25mm air gap from an outer plexiglas pane of similar thickness. Additional insulation is provided by externally cladding the bottom and sides of the tank with 25 mm, high density styrofoam sheeting. The water surface forms the lower boundary of a low speed wind tunnel, which extends 0.5 m above the maximum water surface depth of 0.5 m. A constant heat flux for the lateral boundary is produced by radiant heating. A set of 4 lamps is housed at the closed end of a reflective enclosure, and aligned to point towards the opposite, open end of the enclosure. At present a maximum flux of approximately 100W m^{-2} is produced.

A typical profile representative of the initial stratification conditions is shown in Figure 2.2.1. As we have no way of imparting constant heat and salinity fluxes at the top and bottom boundaries to maintain the initial gradients, we have opted to deliberately include constant temperature and salinity layers there. The depth of these layers is sufficiently large so that transport of heat and salt down the gradient will only produce small changes of temperature and salinity at the top and bottom. In this way the central sections of the gradients will continue to approximate the initial profiles for a longer period of time.

Figure 2.2.1: Typical initial T,S, and ρ profile

Fast response thermistor and conductivity probes are used to obtain vertical temperature and salinity profiles. The instruments used are Thermometrics FP07 thermistors and Precision Measurement Engineering 4-electrode conductivity sensors. Both instruments have spatial resolutions of less than 1mm. A thermistor / conductivity probe pair is mounted at the end of a chrome-alloy plated airfoil section which is driven vertically by a small DC motor. Vertical position is determined using a linear potentiometer. The assembly is carriage mounted and may be manually positioned along

the centerline (x-direction) of the facility. To measure a profile, the airfoil is driven down through the water column at approximately 10 cm s^{-1} and the output of each probe and the potentiometer is sampled at 100hz. Data acquisition is accomplished with a Macintosh II computer and National Instruments LabVIEW software.

For flow visualization and velocity measurements we have developed techniques which are based on video recording the flows, and later processing the images using software developed in the laboratory. For flow visualization, injections of small quantities of Rhodamine-B and Fluorescein dye have been used. The dye is viewed in a vertical plane produced normal to the sidewall by passing a 1W laser beam through a glass rod and then directing the sheet through a thin slit in the external insulation at the bottom of the tank. This is shown schematically in Figure A.2.2, and typical images of the flow using this technique are shown in Figure 2.2.2.

Finally, as a precursor to commencing experiments with wind forcing we have developed a vortex-shedding anemometer for accurately measuring the flowfield in our low-speed windtunnel. We are forced to use the vortex-shedding device, because at low wind speeds hot-wires tend to convect and produce erroneous measurements. Tests of this technique have proved it to be most satisfactory.

Figure 2.2.2: Flow Visualization of a Regime I Type Image

2.2.2 Numerical Facilities

For the purpose of doing our numerical simulations, we modified the SEAFLOS1 code which has been developed at Stanford (Perng and Street, 1989). The code solves, in two dimensions, the finite differenced forms of the unsteady mass, momentum, energy and species conservation equations on a spatially non-uniform grid. Though having its origins in the SIMPLE algorithm (Patankar 1980), SEAFLOS1 differs in some fundamental respects. These differences relate primarily to the use of quadratic upstream interpolation for the convective terms and a conjugate gradient scheme for the solution of an exact pressure equation. Time advancement is by an explicit, second-order predictor-corrector scheme. In addition, the Boussinesq approximation has not been invoked insofar as the effect of temperature and salt concentration on density, and all other fluid properties, has

been explicitly retained. Pressure is decomposed so as to remove the effect of the hydrostatic component. This code has previously been used to simulate time varying, natural convection flows in cavities (Schladow, Patterson and Street 1989; Schladow, 1990).

2.3 THEORETICAL WORK

The general evolution of the intrusions is common to all experiments. Initially small roll cells develop along the heated wall. In time these become more elongated and take the form of a series of relatively well-mixed layers separated by sharp density interfaces. At a later time they thicken by merging with neighboring intrusions. Within each layer, strong shear is created along the interfaces by flow moving away from the wall in the upper region and back towards the wall in the lower region. Shear velocities are $O(1 \text{ mm s}^{-1})$, while the front of the intrusion advances with a velocity $O(10)$ times smaller. Motions near the sidewall are also generally common to all experiments. A parcel of fluid very close to the sidewall rises until the salinity retained by that parcel inhibits any further upward motion. The parcel is then forced out away from the wall, cools off, becomes heavier than the surrounding fluid, and falls back down until it is again entrained by flow towards the sidewall. This process continues as the initial convective cells combine to form larger intrusions. The specific flow behavior and structure of the intrusions vary significantly, however, depending on the stability of the system.

The primary focus of our theoretical work was to develop a scaling algorithm to estimate the height of the intrusive layers (h) at the initiation of the (intrusive) flow. Our goal was to develop a more consistent scaling than that proposed by Narusawa and Suzukawa (1981) who suggested that

$$h_{ns} \sim [(\nu\kappa_T)/(\alpha(q/k))]^{1/4} \quad (2.1),$$

where h_{ns} is the layer height, q is the heat flux at the wall, κ_T is the thermal conductivity, α is the coefficient of thermal expansion, ν is the kinematic viscosity, and g is the gravitational acceleration. This scale is relevant at the onset of convection, prior to any merging events, and carries the implicit assumption that the horizontal and vertical length scales are identical. Of particular note is the fact that (2.1) is independent of the ambient stratification conditions!

In classifying our experiments two dimensionless quantities can be shown to capture the key force balances. These quantities are the Rayleigh ratio, R_p , and the lateral ratio, R_l , which are defined as follows:

$$R_p = (\beta\partial S/\partial y)_i / (\alpha\partial T/\partial y)_i \quad (2.2), \text{ and}$$

$$R_l = -(\alpha(q/k)) / (-\alpha\partial T/\partial y + \beta\partial S/\partial y)_i \quad (2.3).$$

R_p is a measure of the initial stability of the stratification: large values of R_p indicate weak double diffusive effects and large gravitational stability. R_l is a measure of the lateral temperature gradient: a large value of R_l indicates a strong lateral forcing and weak vertical stability.

In our analysis we consider the boundary region of the present system and make the usual boundary layer assumption that the velocity and length scales normal to the dominant flow direction (u and δ) are much smaller than the length scales in the flow direction (v and h). At time $t=0$ a constant heat flux is applied, and heat is conducted to a thermal boundary layer with thickness $O(\delta_T)$ given by

$$\delta_T \sim \kappa_T^{1/2} t^{1/2}. \quad (2.4)$$

Initially, buoyancy acts to accelerate the fluid within the boundary layer. Comparing the unsteady and viscous terms of the vertical momentum equation gives the ratio of these two terms to be $O(Pr^{-1})$, suggesting that at this stage the correct balance within the boundary layer is between buoyancy and viscosity. The buoyancy term may be expressed as

$$g' = (\rho'/\rho_0)g = (-\alpha T' + \beta S')g \quad (2.5)$$

where T' is the perturbed temperature and S' is the perturbed salinity due to motion and diffusion.

Once the heat convected vertically is the same as the heat conducted in from the boundary, (i.e. advection and diffusion terms of the energy equation are balanced) the boundary layer thickness will remain constant and the vertical scale will continue to increase. The rising fluid will eventually reach a maximum height and stop. At this point $g' = 0$ and $y = h$ giving the following result for h ,

$$h \sim R_l N^{-1} K_T^{1/2} Pr^{1/4} \quad (2.6)$$

Equation 2.6 also brings to light a problem. Because the boundary layer analogy we are employing requires that $\delta < h$, it implies that the above analysis is only applicable for cases where $R_l > 1$. The correct force balance for the converse case is not yet apparent. Results of our numerical simulation shed little light on the problem, although it appears to suggest that the vertical length scale in a case with $R_l < 1$ is strongly influenced by high velocities produced by double diffusive instabilities. This is an issue we propose to pursue in the future.

2.4 EXPERIMENTAL WORK

Experiments were performed with the goal of obtaining a set of baseline data representative of the stability and dynamics of a two component linearly stratified system subject to lateral heating. System stability is characterized by the two dimensionless parameters, R_l and R_ρ , defined by equations 2.2 and 2.3. Generally, a large value of R_l indicates strong lateral forcing and weaker lateral stability, while a large value of R_ρ indicates weak double diffusive effects and greater gravitational stability. Experiments have been conducted over a wide range of R_l and R_ρ values (see Figure 2.4.1) in order to monitor the flow behavior for a variety of stability conditions.

Three regimes of intrusions have been defined, based upon the initial values of R_ρ and R_l in each experiment. The orientation of each regime in the R_l - R_ρ plane is shown schematically in Figure 2.4.1. The intrusions are distinguished by their characteristic dimension (h), propagation velocity (u), internal temperature and salinity fields (T and S), as well as by their ability to continue propagating after the heat flux is removed. The characteristics of the intrusions are summarized in Table 2.1. Photographs and sample profiles for Regimes I, II, and III (profile only) are not shown here but are shown in the attached paper in Appendix A.3 as Figures 6, 7, and 8 respectively. The step-like nature of the profiles indicates the presence of the horizontal intrusions or convecting layers. As noted in Table 2.1, however, the distinguishing characteristic of Regime III flows is that the intrusions are self-perpetuating (they continue to propagate out away from the sidewall after the applied heat flux has been removed), whereas the intrusions in Regimes I and II are not self-perpetuating, but simply diffuse away following removal of the sidewall heat flux.

Figure 2.4.1: Summary of experiments completed to date in the R_l - R_ρ plane. Each $\circ$ represents the initial conditions of one experiment.

2.5 NUMERICAL WORK

One numerical case has been considered to date. It has initial temperature and salinity gradients of $83.3^\circ\text{C}/\text{m}$ and $17.9\%/ \text{m}$ respectively, and a sidewall heat flux of $100\text{W}/\text{m}^2$. This produces a flow with $R_\rho=5.0$, and $R_l=0.5$. This case was chosen because it is realizable despite the very resource intensive (5 s of CRAY X/MP time for every 1/80s computational timestep!) demands of the computations. Unfortunately, the case chosen is not covered by the scaling analysis and is very difficult to do experimentally. However, despite the fact that the solution has not been advanced to the stage where merging would be expected, the results do conform with the experimental results in this general parameter range (Regime I), and it is possible to make some observations regarding the early stages of layer formation.

Regime	Final h (mm)	u (cm/hr)	T	S	Self-Propagating?
I	<10	5-10	stably-stratified	well-mixed	no
II	10-40	10-30	stably-stratified	well-mixed	no
III	30-50	>25	well-mixed	well-mixed	yes

Table 2.1: Characteristics of the Intrusions

Two figures, first shown in Thomas et al. (1989) are reproduced here. Figure 2.5.1a shows profiles of temperature and salinity 180s after commencement of heating. The profiles are taken 1.5mm ($x/l=0.018$) from the sidewall. The step-like structure of the intrusions is clearly evident in these profiles. Note, that as in the experimental results, salinity is well-mixed whereas an inverse temperature gradient has been established within each intrusion. The profile of horizontal velocity at the same location and time is shown in Figure 2.5.1b. The numerical results differ from experiments for Regime I in that the intrusions are much thinner and they develop far sooner.

A more detailed examination of the horizontal profiles of T, S, u and v along the $y/h = 0.5$ section (see Figures 10-12 in Appendix A.3) shows that the formation of the intrusions is seen to pass through an initial sidewall convection stage at $O(10s)$, an initial instability producing a vertical flow reversal at $O(20s)$, a "fingering" period from 20-100s, followed ultimately by intrusions dominated by horizontal flows out along the top and in along the bottom. The fingering period may be of special significance. As mentioned above, the thickness of these "fingers" is about 1mm suggesting a timescale for diffusion of heat of about 10s. Therefore, heat could conceivably diffuse (producing the relatively smooth temperature profiles), whereas the salt, with effectively no diffusion, drives the convective flow. In fact the vertical velocities associated with the "fingering" are considerably larger than those associated with the sidewall convection. In addition, there are indications that the vertical thickness of the layers for cases of $R_l < 1$ may be related to the dynamics of the "fingers". Additional results from the numerical simulation are provided in Appendix A.3.

Figure 2.5.1: Vertical profiles from numerical simulation of Regime I flow. (a) temperature (in bold) and salinity :
(b) horizontal velocity

3. WORK IN PROGRESS

In this section we review the work that is currently being performed and that will be essentially complete at the end of the present funding period in August 1990.

3.1 MODIFICATION OF FACILITIES/INSTRUMENTATION

Heated Side-Wall: A constant heat flux for the lateral boundary is produced by radiant heating using a set of 4 lamps housed at the closed end of a reflective enclosure (see Sec. 2.2.1). At present a maximum flux of approximately 100W m^{-2} is produced which is insufficient for the planned experiments. A new system is being built which will give us a wider range of heat flux at the boundary. This will enable us to explore a larger portion of the R_ρ - R_l stability domain (see Figure 2.4.1).

Horizontally Traversing Probe: At present our temperature-conductivity probe can only traverse the flow in the vertical direction at fixed distances from the heated wall. Because our future work will focus on the internal structure of the horizontal intrusions, it is essential that we traverse these intrusions in the horizontal direction at a fixed height. The design of our probe will be based on that developed by John Taylor at the University of Western Australia in Perth.

Vortex Shedding Anemometer: As a precursor to commencing experiments with wind forcing we have had to develop a means of accurately measuring velocity profiles in our low flow wind tunnel. To this end we have been working towards the design and construction of a vortex shedding anemometer (see Roshko, 1954 and Scotti and Corcos, 1972). Testing of the method has been carried out to our satisfaction, and we are about to commence construction of a more refined version of the instrument.

Temperature Measurement: Our initial profiling experience has shown us that the response of the Precision Measurement Engineering 4-electrode conductivity sensor to changes in temperature is much more rapid than that of the Thermometrics FP07 thermistor itself. This results in a greater degree of uncertainty in our estimate of salinity than we feel is acceptable. Consequently, we are investigating the use of more rapid response temperature sensors such as platinum wire thermometers.

3.2 EXPERIMENTAL WORK

In addition to the experiments performed to date, we intend to complete the following program by the end of the present research period. Firstly, the sidewall heating system will be modified such that a wider range of heating rates may be applied to the sidewall. This modification will allow us to perform experiments over the entire range of the R_ρ - R_l plane, filling in the gaps which require heating rates unattainable with the present heating apparatus. By completing these experiments we hope to further isolate the conditions for which "self-propagation" of the intrusions occurs, as well as enhance our understanding of the physical mechanisms governing the release of potential energy which drives these intrusions. Furthermore, these experiments will provide us with additional insight into the merging process within each flow regime, as well as the significance of fingering motions to the development of the intrusions (discussed in more detail below).

Secondly, to supplement the acquisition of vertical temperature and salinity profiles through the intrusions, we are presently designing a probe which may be driven horizontally through the intrusions, thus providing us with horizontal profiles of temperature and salinity. From these profiles, we can extract a great deal of information regarding the structure and behavior of the fingers, which have formed in previous experiments as observed from flow visualization. In particular, the vertical fluxes of heat and salt can be estimated from the horizontal temperature gradient through the fingering

region. This estimate of the fluxes can then be compared to the fluxes as determined by direct measurements of temperature and salinity (from vertical and horizontal profiles) and velocity (from particle tracking). If successful, these experiments will be extremely helpful in assessing the importance of the unsteady term in the governing energy equation. This term is neglected in the horizontal gradient technique and can lead to underestimation of the fluxes by as much as 56% (Gargett and Schmitt (1982), Taylor and Bucens (1989)).

In addition to the above studies, several experiments will be performed in order to complete quantification of the heat losses through the side, bottom, and top of the double diffusion facility. The experiments will be similar to those carried out by Munoz and Zangrando (1986) and will require two individual experiments to separate the sidewall losses from the bottom and top losses. In each of the experiments, thermistors and thermocouples will be distributed throughout the facility in order to carefully monitor the temperature of the water, as well as the ambient air. The water will be maintained at a constant temperature by heaters which supply a known amount of heat to the water mass. By applying a simple energy balance, the losses can then be determined.

3.3 NUMERICAL WORK

The numerical work to date has been performed by Dr. Geoff Schladow who was, until recently, a Research Associate at Stanford. We are continuing with the development of the numerical scheme (SEAFLOS1) at Stanford under the direction of Professor Street, and are implementing it on the Culler mini-Supercomputer at the University of Washington (UWA). In addition, Dr. Schladow is currently continuing numerical simulations at no cost to UWA. Therefore, in order to increase our numerical capability we are implementing SEAFLOS1 on a Culler mini-Supercomputer within the Center for Water Research at UWA. Professor Koseff will be visiting UWA for 5 months on sabbatical in 1990. Dr. Schladow on the numerical simulations. Having SEAFLOS available on the Culler mini-Supercomputer, therefore, essential to this effort.

The Culler mini-Supercomputer, which operates at 10MFlops, will be upgraded to 70MFlops and 5 processors by June 1990. This will elevate the machine to the realm of CRAY X/MP. Data processing is done on a system of Sun Workstations. In addition we are working on the following tasks:

- (a) System testing to ensure consistency of present simulation results with earlier simulations.
- (b) Graphics development.
- (c) Simulating flows in each of the flow regimes identified experimentally to date. The simulations are being conducted for a sufficiently long time to allow merging phenomena to occur.
- (d) Preliminary analysis and interpretation of simulation results. The aim here is to replicate the experimental results and to *identify* the mechanisms of intrusion formation and propagation (e.g., what causes merging in Regime II).

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