Progress Report
for
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FLUID DYNAMICS OF DOUBLE DIFFUSIVE SYSTEMS

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PROJECT SUMMARY

A study of mixing processes in doubly diffusive systems is being conducted. Continuous gradients of two diffusing components (heat and salinity in our case) are being used as initial conditions, and forcing is introduced by lateral heating and surface shear. The goals of the proposed work include: (1) quantification of the effects of finite amplitude disturbances on stable, double diffusive systems, particularly with respect to lateral heating, (2) development of an improved understanding of the physical phenomena present in wind-driven shear flows in double diffusive stratified environments, (3) increasing our knowledge-base on turbulent flow in stratified environments and how to represent it, and (4) formulation of a numerical code for such flows. The work is being carried out in an experimental facility which is located in the Stanford Environmental Fluid Mechanics Laboratory, and on laboratory minicomputers and CRAY computers.

In particular, our overall goals are as follows:

- 1) develop more general stability and scaling criteria for the destabilization of doubly-stratified systems,
- 2) further study the variation of flow structure and scales with Rayleigh ratio and lateral heating ratio,
- 3) further delineate the mechanisms governing convective layer formation and merging,
- 4) study the mixing processes within the convective layers and across interfaces, and estimate the heat and mass fluxes in such a system,
- 5) quantify the effects of turbulence and coherent structures (due to a wind-driven surface shear) on a doubly stratified system, and
- 6) study the interaction between surface shear and side-wall heating destabilization mechanisms.

PROJECT GOALS FOR THE PERIOD AUG 1 1990 TO JULY 31 1991

The goals of the project for this period were as follows.

a. Physical experiments

1. Previously, we had performed a set of experiments over a range of stability parameters, R_ρ and R_l , and had classified the type of intrusions that formed using these parameters. Our goal was to extend the range of R_ρ and R_l over which the intrusion structure is studied.
2. We wished to complete the development of more general stability and scaling criteria for the destabilization of doubly-stratified systems.
3. We had begun to modify the wind-tunnel portion of the facility and to develop appropriate instrumentation for this part of the facility. Our goal was to complete this aspect of the work and to begin experiments using the wind to destabilize the system.

b. Numerical experiments

4. We had successfully completed a two-dimensional simulation of a Regime (now referred to as Class) I case. Our goal was to extend these simulations to Class II and Class III type conditions, and to investigate the role of boundary conditions on the stability of the system.

PROGRESS TO APRIL 1 1991

A great deal of progress has been made in the past 7 months in all the experimental aspects of the project outlined above. We have altered our strategy where appropriate, and have performed experiments and studies not described in our project proposal. The details of our progress are outlined next.

Experimental Program

Scaling: Additional experiments have been performed over a wider range of stratification conditions than reported previously. Modification of the endwall heating system through the use of more efficient and powerful lighting provides us with a much greater range of heat flux values at the heated endwall. Thus, experiments can now be performed for a much wider range of R_ρ and R_l . The outcome of the additional experiments performed to date has been consistent with expectations, based on previous results. For $R_l \gg 1$ (relatively high endwall heating rates), the endwall heating controls the initial thickness of the intrusions. This characteristic was shown to be true for a case in which the initial vertical stratification was quite stable ($R_\rho = 9$), a result which was predicted by the scaling analysis but could not be verified experimentally prior to the improvements to the endwall heating. Indeed, all additional experiments carried out for $R_l \gg 1$ produced initial intrusion thicknesses consistent with the scaling analysis. Fig 1 presents a comparison of our experimentally measured initial intrusion thicknesses (h_{obs}) with our theoretically derived thickness scale (h). Theoretical scales derived by Tanny and Tsinober (1988) (h_{CT}), and Narusawa and Suzukawa (1981) (h_{NS}), are also presented for comparison purposes. For $R_l \gg 1$, the points representing our proposed lengthscale, h (dark circles in figure 1), are clustered near the dashed 45 degree line which represents the condition $h=h_{obs}$ (i.e. perfect agreement). This indicates that our scaling is indeed valid.

The scaling proposed by Tanny and Tsinober (h_{cr}) shows a similar trend, but gives a larger error than h and consistently overpredicts h_{obs} . The scaling proposed by Narusawa and Suzukawa is not consistent with h_{obs} for $R_l \gg 1$.

Internal Structure: A new horizontal traversing mechanism has allowed us to obtain horizontal temperature and salinity profiles in addition to those taken vertically. These horizontal profiles provide detailed quantitative information regarding the horizontal structure of the intrusions, which may be compared with the qualitative results of flow visualization, as well as the numerical simulations. Sample horizontal temperature and salinity profiles are shown in Figure 2 for a Class II experiment. The profiles shown in Figure 2 were taken at the depths (in cm) indicated on the figure and span the range of one intrusion thickness (depth). As can be seen from this figure, the temperature and salinity signals vary quite markedly over the depth of a single intrusion.

Wind-Tunnel Modifications: We have worked on (and continue to work on) improving the steadiness of the tunnel and spatial homogeneity of the velocity distribution. Our goal is a wind speed which is invariant throughout the experiment, and a wind velocity profile which resembles a typical flat plate boundary layer profile, and which is invariant across the span of the facility.

Our first measurements made with our vortex-shedding anemometer (see below) have shown that the wind speed at a point increased by about 45% over an hour and 65% over ten hours. We have identified the cause to be the fan controller: the elements in the controller box became warmer over the course of an experiment causing the power to the fan to vary. We have found that heating the controller above the ambient lab temperature achieves the steady running speed faster and keeps the velocity fluctuations within 1% once the steady state has been reached (figure 3). However, since we require the wind to be constant from the start of the experiment, we will re-route the flow through a vent in the downstream section of the tunnel until the transient behavior has diminished. We are also considering a computer feedback control which would monitor the velocity in the tunnel and adjust the fan motor to maintain a constant speed.

Our velocity profiles, at present, indicate significant (unwanted) vertical and transverse velocity variations (Figure 4). In particular, a profile on the centerline shows a bulge near the tunnel bottom of about 10% of the mean velocity. This problem has since been traced to defects in the screens and honeycomb sections used to condition the flow. We have improved the situation somewhat by installing coarse grids in the flow conditioning section (see Figure 4b), and we are presently testing different arrangements of the screens and honeycomb to improve the profiles.

Development of Techniques

Particle Imaging Velocimetry: We currently measure velocity fields by calculating velocities from particle "streak" lengths. These "streaks" are created by adding video frames taken at fixed time intervals apart together, color coding each particle making up the streak for directionality, and computing the length of the streak. Typically, four images are used and a "streak" is validated by checking that it has a contribution from all four images. Therefore, if a particle moves in or out of the image plane during the imaging period then the "streak" it creates will not be used. This technique is, therefore, very inefficient. A new technique for computing 2-D velocity fields from particle images (Willert and Gharib, 1991) which is significantly more reliable than the method previously employed is currently being adapted. The new technique utilizes correlations of the movement of groups of particles to produce velocity vectors, rather than following individual particle "streaks" as in the previous method. This technique allows us to seed the flow with many more particles and significantly improves both the accuracy and resolution of the velocity fields.

Thermistor Response Time: In order to measure salinity we use a conductivity probe. The probe is sensitive to temperature changes as well and it is, therefore, necessary to have temperature measurements as well to deduce the salinity. It is imperative, therefore, that both sensors respond in the same fashion to changes in temperature. Experiments were carried out in order to quantify the response time of the FP07 thermistor as a function of probe traversing speed. These results are used as input to a digital filter which sharpens the temperature response so that it more closely matches the nearly instantaneous response of the conductivity probe. In order to obtain a sharp temperature gradient over which the response could be measured, the thermistor was electronically overheated as the probe travelled through water of a constant temperature. The time required for the thermistor to return to this ambient temperature is a measure of the response time of the instrument. A plot of the response time (3dB) as a function of probe speed is shown in Figure 5. As expected, higher probe speeds produce faster response times. For a probe speed of 12 cm/sec (typically used for vertical profiles in the experiments), the thermistor response time is approximately 3.8 msec and can be sharpened so as to minimize time-response mismatch errors between the temperature and conductivity signals.

Vortex-Shedding Anemometer: Because the wind speeds in our facility will be low (between 0.5 and 3.5 m/s) many of the methods that are available for measuring wind speed are impractical. For example, at low wind speeds hot wires are both inaccurate and inconvenient since they lose heat to free convection and require frequent calibration. Pitot tube measurement also suffers some complications since pressure differences arising from low flows are extremely small (1 m/s gives a pressure difference of 4 microns of water).

Because of these problems, we have chosen another method--vortex shedding anemometry--to measure the wind speed. In studying flow around a circular cylinder, Roshko (1954) observed a stable vortex street for Reynolds numbers between 60 and 150 (based on the cylinder diameter) and proposed a relationship between the wind speed and the frequency at which vortices are shed from the cylinder. To measure the wind speed, we built a probe consisting of a hot film sensor placed in the vortex street of a cylinder. From the sensor output, we can determine the shedding frequency and compute the wind speed. This method has two main advantages over the others: (1) Problems with free convection and calibration vanish since we measure only the frequency--not the magnitude--of the sensor signal, and (2) any speed can be measured as long as the cylinder diameter is chosen to give an appropriate Reynolds number.

However, there are problems with this method. Near the supports of the cylinder, the pressure is greater than at the center of the span. This pressure gradient causes the vortices to be shed obliquely (Figure 6a) and reduces the shedding frequency. Williamson (1989) showed that this problem could be overcome by angling the endplates at the supports to accelerate the flow and eliminate the pressure gradient, and thereby induce parallel shedding (Figure 6b). We have built two refined probes with angled end plates and different cylinder diameters. In addition, we have ordered a high-precision pressure sensor (MKS Baratron) to give an independent check of velocity.

Numerical Simulations

Simulations of flow cases corresponding to all three flow classes identified by the physical experiments have now been conducted. The results have been satisfactory; however, the simulations have not been very extensive as the dynamics of the Class II and Class III flows make the computations extremely resource intensive. Progress has also been slowed because we are busy implementing the code on a Culler super-minicomputer at the University of Western Australia. (Most of the simulations are being performed by Dr. Geoffrey Schladow in Australia.) It is expected that the code will be

running on this computer by the end of April, and progress should be more rapid between May and August.

Papers and Presentations

Schladow, S.G., Thomas, E., and Koseff, J.R., The Dynamics of Lateral Intrusions in a Thermohaline Stratification, *Journal of Fluid Mechanics*, accepted for publication, 1991.

Schladow, S.G., Thomas, E., and Koseff, J.R., Structure of Thermohaline Intrusions – A Comparison of Numerical and Experimental Results, *EOS*, Vol. 71, No. 43, pp. 1360, 1990.

Thomas, E., and Koseff, J.R., and Schladow, S.G., Thermohaline Intrusions in a Two-Component Density Stratified System, *Proc. of Int'l Conf. on Physical Modeling of Transport and Dispersion*, Mass. Inst. Tech., Aug 7-10, 1990, pp. 8C.7-12.

PLANNED PROGRESS TO AUGUST 1, 1991

Our plans for the rest of the funding period can be sub-divided into five categories: (i) continued analysis and interpretation of data from completed experiments, (ii) additional physical experiments using lateral heating, (iii) completion of testing of wind tunnel, (iv) implementation of modifications to the tunnel, and (v) continue with our numerical simulations. As described above we are now able to measure horizontal profiles of temperature and salinity in the intrusions. We are now analysing these profiles in conjunction with our flow visualization data and our numerical simulations to develop a more complete picture of the internal structure of the intrusions. In category (ii) we are planning to perform experiments in the $R_p - R_l$ region not covered by previous experiments. Under categories (iii) and (iv), we are working on improving the flow in the wind tunnel by experimenting with various types and configurations of flow conditioning screens. In addition, we shall be working on eliminating the transient "warm-up" period (see Figure 3) currently observed in the tunnel. Finally, we expect to make more rapid progress on our numerical simulations. Professor Koseff will be spending a sabbatical at the University of Western Australia for six months from July to December 1991, and will be working on the simulations with Dr. Schladow during that period.

PLANS FOR PERIOD AUG 1 1991 TO JULY 31 1992

In general we plan to follow the research program outlined in our original proposal.

Physical Experiments:

Complete experiments with lateral heating, and begin experiments with wind-shear destabilization. Focus initially on flow visualization and a qualitative interpretation of the physics. Continue with analysis of results from both sets of experiments.

Numerical Experiments:

Continue with simulations of lateral heating case over range of R_p and R_l . Extend the simulations to longer times and compare results with theory and physical experiments.

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