# Experimental study on the structure and stability of a double-diffusive interface in a laterally heated enclosure

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**Abstract:**
*Experiments are carried out to investigate the structure of a double diffusive interface separating two layers in a laterally heated enclosure. The main goal of this work is to study the structure of the interface and some of its instability characteristics. The experiments are carried out in a box with inner length, width and height dimensions of 100 × 100 × 92 mm. The velocity field at the vicinity of the interface is measured by a PIV system. Vertical concentration and temperature profiles are measured using a micro-scale conductivity/temperature instrument and the flow is visualized using the schlieren technique. Analysis of mean horizontal velocity profiles, obtained at different times during the experiment, illustrates the increasing tilt of the interface with time. Spectral analyses of velocity perturbations under unstable and stable conditions confirm the existence of the coherent vortices observed by the schlieren technique. The vortices above and below the interface are associated with different dominant frequencies due to the asymmetric character of the flow. Measurements show that the vortices are generated outside the region of the stabilizing concentration profile by a mechanism, which is essentially thermal and similar to Rayleigh-Bénard instability with weak shear.*

**Key-words: Stability; spectra; vortices**

## 1 Introduction

The interface separating two layers of a solute-stratified fluid in a laterally heated enclosure is one of the fundamental double-diffusive systems. For example, when a continuous stable solute gradient is subjected to a lateral temperature gradient (e.g., Chen, Briggs & Wirtz, 1971) an array of convective layers separated by density interfaces is formed. Under certain conditions the layers undergo a sequence of merging events (Tanny & Tsinober, 1989). Evidently, the merging process is controlled by the conditions at the interface separating the layers. Consequently, several research works were focused on the behaviour of a single salinity interface in a laterally heated fluid.

Bergman & Ungan (1988) studied experimentally the behaviour of a two-layer system destabilized by lateral heating and cooling in a box. They pointed out that the interface is simultaneously exposed to shear instability due to the co-rotating circulation in each layer, and to double-diffusive instability due to the stabilizing and destabilizing vertical solute and temperature gradients, respectively. Nishimura *et al*. (1999), using laser-induced fluorescence and particle paths visualization techniques, were able to observe vortices within the interface. In a later study, Nishimura *et al.* (2000) observed travelling plumes that ascend and descend from above and below the interface into the mixed layers. The plumes exhibited a three-dimensional flow structure. Measurement showed that the spacing (in the span-wise direction) and frequency of the plumes decrease and increase, respectively, nearly linearly with the lateral temperature difference.

Tanny and Yakubov (1999) carried out an experimental study in which the stability of the flow adjacent to the interface was examined. Their study revealed that the interfacial flow can be stable or unstable and the stability criterion was determined experimentally in terms of the governing parameters of the problem. Using the schlieren flow visualization technique, they showed that under unstable conditions the flow was characterized by the existence of vortices, moving along the interface above and below it (see Fig. 1 below). On the other hand, under stable conditions no vortices were observed.

From the above review it appears that in the existing literature various mechanisms are suggested for the instability and mixing processes of the two-layer stratified fluid. Still, the mechanism that dominates the onset of interfacial instability and the consequent appearance of vortices, plumes or waves was not identified. In this paper we report on detailed measurements of the structure of the flow and present some characteristics of the flow stability derived from spectral analysis of the velocity field and a series of temperature and concentration profiles measured under a variety of physical conditions. A possible instability mechanism is finally discussed. A more detailed account of this work can be found in Tanny *et al.*, (2005).

## 2 Experimental setup and procedures

A detailed description of the experimental setup and procedures is given in Tanny *et al.* (2005). The experiments were carried out in a box with inner length, width and height dimensions of 100, 100 and 92 mm, respectively. Two sidewalls of the box were made of stainless steel and were provided with passages through which water from two constant-temperature baths could circulate. The two other sidewalls were made of optical glass to facilitate schlieren flow visualization and PIV measurements. The flow was visualized using a schlieren system consisting of two spherical mirrors, a white light source and a knife-edge. Vertical concentration and temperature profiles were measured by a micro-scale conductivity/temperature instrument. Velocity field measurements were carried out using the PIV (Particle Image Velocimetry) technique.

The two-layer stratified system was established by initially preparing two aqueous salt (NaCl) solutions of the prescribed concentrations in two separate beakers and seeding each of them with the glass spheres. The tank was first filled with the lower layer of aqueous solution of the higher concentration. Then, the upper layer of the lower concentration was poured carefully on the lower one (using a wooden float). In most experiments, the prescribed wall temperatures were set in advance in the two circulation baths and the lateral temperature difference was applied almost instantaneously by opening valves that allow the bath fluid to circulate into the passages of the sidewalls. In part of the experiments the temperature difference between the sidewalls of the enclosure was increased stepwise with time, from 3°C up to 24°C, by adjusting the temperatures of the circulating baths.

The parameters that govern the flow are $\Delta C$, the initial concentration difference between the two layers and $\Delta T$, the lateral temperature difference between the two sidewalls. These are represented in a non-dimensional form by the Rayleigh number Ra = $g\alpha\Delta T L^3/\nu\kappa$ where $g$ is the acceleration due to gravity, $\alpha$ is the coefficient of thermal expansion, $L$ is the box width, $\nu$ is the kinematic viscosity and $\kappa$ is the thermal diffusivity, and by the buoyancy ratio, $R_\rho = \beta\Delta C/\alpha\Delta T$ where $\beta$ is the coefficient of solutal contraction.

## 3 Results

Analyses of vertical profiles of the mean horizontal velocity as measured by the PIV system (Fig. 2a) were done to study the time dependent structure of the interface. These analyses clearly showed that at a relatively early stage of the experiment, the interface was slightly tilted. At a later stage of the same experiment, however, a sharp tilt (inclination of about 12°) of the interface was observed. In spite of this sharp tilt, the total interface thickness and the inner layer thickness were nearly uniform along the horizontal.

Spectral analysis is carried out of the instantaneous velocity profiles, measured in an experiment with $\Delta C$ = 0.56%, $\Delta T$ = 22.52°C, which correspond to Ra = $4.46\times10^8$ and $R_\rho$ = 0.66. These conditions correspond to unstable interfacial flow (Tanny & Yaakubov, 1999) and vortices are observed by the schlieren technique in this experiment.

The present schlieren images (see an example in Fig. 1), as well as the photographs of Tanny & Yakubov (1999) show that the vortices move above and below the interface, in a direction associated with the convective circulation in each layer, *i.e.*, the vortices above the interface move from the cool to the warm sidewall and those below it from the warm side wall to the cool one. Fig. 1 shows that at their generation the vortices are relatively small but while moving along the interface, they gradually grow in size until they hit the opposite cool/warm sidewall.

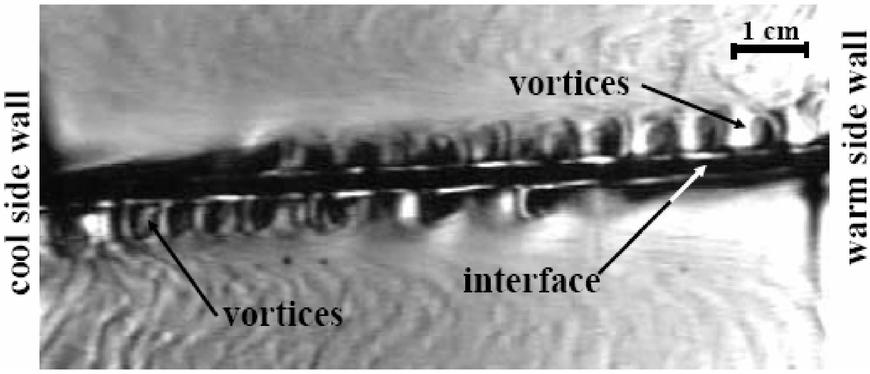


*Figure 1: A schlieren image of the vortices at the interface. Experimental conditions are: Ra = $4.46\times10^8$, $R_\rho$ = 0.66.*

Thus at the interface and along the horizontal direction, a region may be found where vortices exist below the interface but not above it (e.g., near the cool sidewall, Fig. 1), and vice versa. This raises the possibility that the instability associated with one side of the interface only weakly depends on that of the other side. On the other hand, away from the sidewalls, at the middle of the box, Fig. 1 suggests that vortices exist simultaneously on both sides of the interface. To check this possibility, spectral analysis of the time dependent velocity field measured across the interface near the cool sidewall as well as at the middle of the box, is carried out. Figure 2a shows the vertical profiles of mean horizontal (U, squares) and vertical (V, circles) velocities, measured across the interface near the cool sidewall. Both mean velocities are normalized by $U_m$, the maximum horizontal velocity. The normalized depth, $Y/\delta_m$, (vertical axis) is measured above or below the center of the velocity interface where $\delta_m = |Y_{vm} - Y_{vi}|$, $Y_{vi}$ is the vertical location of velocity interface and $Y_{vm}$ is the vertical location in the outer region where $U = 0.5U_m$.

The associated averaged power spectra obtained from a set of instantaneous velocity measurements, above and below the interface, are shown in Figs 2b and 2c, respectively, as a function of the Strouhal number, $St= f\,\delta_m/U_m$ where $f$ is frequency. The averaged power spectra are calculated by averaging the local spectra over all measurements positions above or below the velocity interface location ($Y_{vi}$). The maximum power obtained from the $u$ and $v$ spectra is used to normalize both.

A significant difference between the shape of the horizontal mean velocity profile above and below the interface near the cool sidewall is observed (Fig. 2a). The flow above the interface has just arrived from the cool sidewall and consists of flow without vortices, characterized by a relatively narrow “nose”. On the other hand, the flow below the interface arrives from the opposite warm sidewall and is already developed, consisting of vortices which make the velocity “nose” thicker than that above the interface, due to the enhanced mixing.

The above observations are reflected by the power spectra corresponding to the regions above (Fig. 2b) and below (Fig. 2c) the interface. While the spectra above the interface are almost uniform, the spectra below the interface show significant amplification of energy over a wide band of *St* (0.2-1.3, corresponding to the frequency range 0.05 – 0.3 Hz) with a distinct peak at about *St* = 0.57 (*f* = 0.13 Hz). Although the magnitude of the mean vertical velocity is much lower than that of the mean horizontal component, their associated power spectra shapes (below the interface, Fig. 2c) are very similar and their magnitudes are about the same, indicating the existence of coherent vortices in this region.

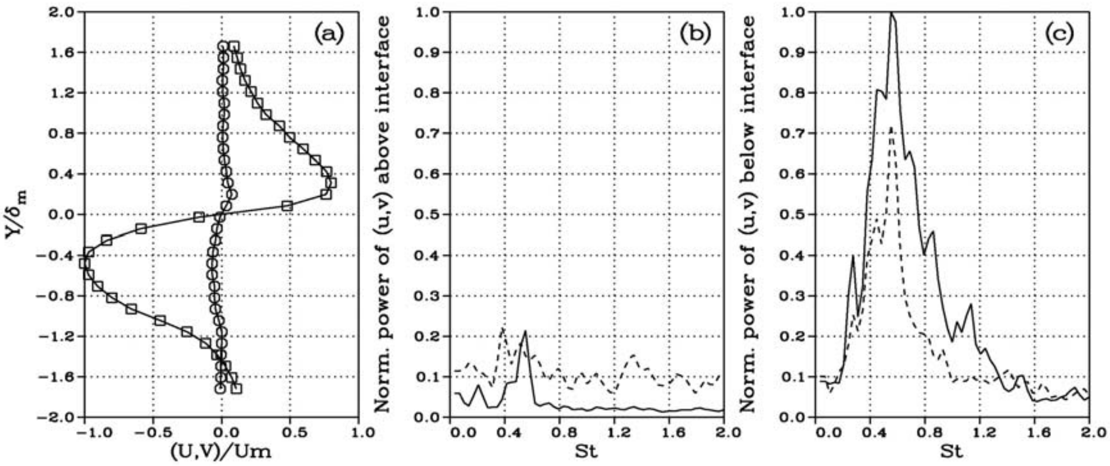


*Figure 2: (a) Vertical profiles of the mean horizontal (squares) and vertical (circles) velocities (normalized by the maximum absolute value of the horizontal mean velocity) for Ra = $4.46\times10^8$, $R_\rho$ = 0.66, t = 72 min, near the cool sidewall. Normalized average power spectrum of the horizontal (dashed line) and vertical (solid line) velocity perturbations above (b)and below (c) the interface as a function of the St number. $U_m$ = 1.38 mm/s; $\delta_m$ = 6.06 mm.*

Spectra were also calculated from PIV data acquired at the same experiment as Fig. 2 but at the middle of the box, approximately in between the cool and warm sidewalls. The results show that the dominant frequency above the interface is about 0.11 Hz whereas below the interface it is about 0.15 Hz. It was also observed that in the region slightly closer to the warm sidewall, the energy peak above the interface is larger than that below it. At the intermediate region the two peaks, above and below the interface, have about the same value and in the region slightly closer to the cool sidewall the spectrum peak below the interface is significantly larger than that above it. These results support the schlieren observation (Fig. 1) that the vortices grow as they travel towards the warm (cool) sidewall above (below) the interface.

In Fig. 3 we illustrate the structure of the flow through an example of velocities, concentration and temperature profiles measured under conditions of unstable interfacial flow with vortices. The vertical axis in each figure (3a, 3b and 3c) is $Y = Y_d - Y_{vi}$. (Note that the vertical center of the concentration interface is slightly shifted). Black-filled symbols are measured values and open symbols are values corrected for optical distortion due to refractive index spatial variations (for more details see Tanny et al., 2005).

It can be seen that the thickness of the inner velocity layer (Fig. 3a) is approximately equal to that of the inner temperature layer (Fig. 3b), and both are about twice that of the inner concentration layer (Fig. 3c). Outside the inner stabilizing concentration layer but within the inner velocity and temperature layers, (approximately within the ranges -3 < Y < -1.5 and 1.5 < Y < 3) the concentration on each side of the interface is almost uniform, whereas the temperature has a destabilizing effect which may induce instability phenomena at these regions. On the other hand, at the outer velocity regions, due to the inflection points in the outer parts of the horizontal velocity profile (at about $Y = \pm 7$ mm), the velocity profile may have a destabilizing effect. However, in these outer regions on both sides of the interface, the temperature increases monotonically with height and consequently stabilizes the flow. These observations support the schlieren visualization of the formation of vortices adjacent to the interface on each side of it (Fig. 1).

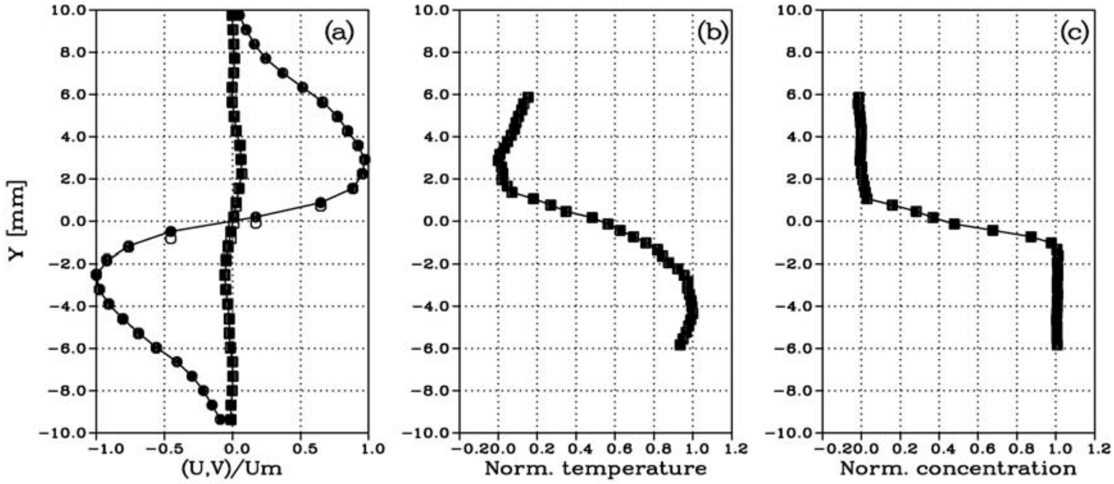


*Figure 3: The structure of the interface. (a) Vertical profiles of the mean horizontal (circles) and vertical (squares) velocities (normalized by the maximum measured horizontal mean velocity) in an experiment with $Ra = 4.46\times10^8$, $R_\rho = 0.66$, $t = 18$ min. Vertical profiles of normalized temperature (b) and concentration (c) for similar conditions as (a). Temperature and concentration are normalized by their corresponding maximum differences across the interface*

The above observation suggests that regions of positive density gradient (hydrostatic instability), caused by the combination of a uniform concentration profile and a negative temperature gradient are associated with the onset of vortices above and below the interface.

The ratio between the thicknesses of the concentration and temperature layers, $\delta_C/\delta_T$ is plotted in Fig. 4 as a function of the local buoyancy ratio, $R_{\rho l}$, defined on the basis of the vertical temperature difference measured across the interface in each profile ($\Delta T_i$) and the corresponding instantaneous concentration difference between the two layers. In this experiment successively decreasing values of $R_{\rho l}$ were realized by the stepwise increase with time of the horizontal temperature difference while allowing the concentration step to decrease by solute diffusion through the interface. Thus, higher values of $R_{\rho l}$ represent more stable conditions.

The data points in Fig. 4 show two distinct regimes with a sharp transition between them, at $R_{\rho l} \approx 7.5$. At relatively high values of $R_{\rho l}$, the ratio $\delta_C/\delta_T$ is high (> 0.5) whereas at lower values of $R_{\rho l}$, $\delta_C/\delta_T$ is much smaller (< 0.325). It is recalled that high values of $\delta_C/\delta_T$ are associated with relatively thin layers of positive density gradient resulting in a stable interfacial flow; indeed, for $R_{\rho l} > 8.5$ no vortices were observed at the interface by the schlieren technique (square symbols in Fig. 4). On the other hand, small $\delta_C/\delta_T$ corresponds to less stable conditions and the observations showed that for $R_{\rho l} < 7$ the interfacial flow was characterized by vortices (circle symbols in Fig. 4). The transition from stable to unstable interfacial flow, at $7 < R_{\rho l} < 8.5$, was characterized in most cases by faint vortices above and below the interface (× symbols in Fig. 4). These findings suggest that the interfacial flow becomes unstable through a mechanism, which is essentially thermal and similar to Rayleigh-Bénard convection (with a weak velocity shear). As the layer with the positive density gradient becomes thicker, the value of a local Rayleigh number increases, the flow may become unstable, and transverse, two-dimensional vortices can emerge.

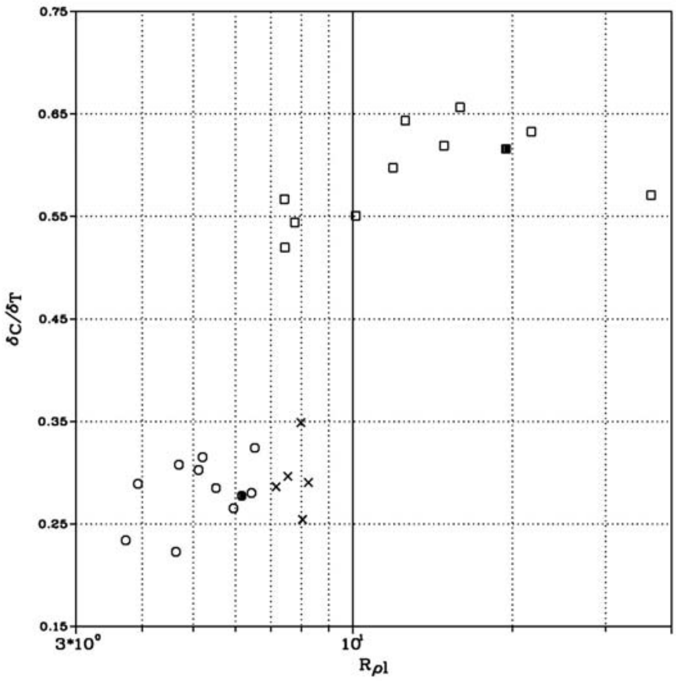


*Figure 4: The thickness ratio between the concentration and temperature gradient layers, $\delta_C/\delta_T$, as a function of the local buoyancy ratio, $R_{\rho l}$. □, no vortices (stable); ×, faint vortices (transition);* O*, vortices (unstable).*

## 4 Conclusions

The main conclusions of this study are: (1) The major instability mechanism causing the appearance of transverse vortices above and below the interface is essentially thermal and similar to Rayleigh-Bénard convection with weak shear. The double diffusive and shear driven instability mechanisms do not seem to play an important role.
(2) The instability phenomena above and below the interface seem to be independent, probably due to the central stabilizing sharp concentration gradient.

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