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Heat and mass fluxes across density interfaces in a grid-generated turbulence

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Abstract

We present heat and salt fluxes measurements across a single density-stratified interface in a grids-generated turbulence system. The turbulent field is measured in a homogeneous medium (water) by Particle Image Velocimetry (PIV). Stratifications have been followed in time by recording the vertical temperature and density profiles. Measured buoyancy heat and mass fluxes show two different behaviors similar to that in double diffusive convection systems. This was also highlighted by measurement of entrainment rate near the interface, which showed that entrainment depends on the diffusivity for high Richardson number *Ri*. For low *Ri*, molecular diffusion has less effect on the transport process than turbulent mixing.

Keywords: Heat and mass transfer; Stratified flows; Density interface; Grid turbulence; PIV measurements

1. Introduction

Mixing across a density interface in stratified flows has been investigated in natural as well as industrial situations because of its importance in the vertical transport of different species across such interfaces [1–4]. Huppert and Turner [5] reviewed the many geophysical and industrial applications of these flows, commonly called *double-diffusive convection*. Their fundamental characteristic is the formation of a system of two horizontal homogeneous layers separated by sharp diffusive interfaces of linear density. In most such situations, the characteristic length and velocity scales are large, ensuring a turbulent flow everywhere that maintains well-mixed layers, sharpens the interface, and produces mixing across the density interface. The vertical transport of different species between the turbulent mixed layers is thus influenced by mixing across the density interface.

The ways in which turbulence is generated in the laboratory vary from one study to another, often because of the specific phenomena studied. In general, two kinds of experiments are used: turbulence generated by mean shear flow and turbulence generated by grid oscillation with zero mean shear. According to Turner [6], the vertically oscillating grid is the more appropriate way to generate turbulence: one or a pair of grids is oscillated vertically in an initially stably density gradient or in

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Nomenclature

A_{int}	interfacial area (m^2)
A_{losses}	surface heat losses (m^2)
c_p	constant-pressure specific heat ($J\,kg^{-1}\,K^{-1}$)
f	grid oscillation frequency (Hz)
F_S	interfacial flux of salt ($kg\,m^{-2}\,s^{-1}$)
F_T	interfacial flux of heat ($W\,m^{-2}$)
F_{SP}	salt flux across a solid plate ($kg\,m^{-2}\,s^{-1}$)
F_{TP}	heat flux across a heated solid plate ($W\,m^{-2}$)
g	gravitational acceleration ($m\,s^{-2}$)
h_l	lower layer depth (m)
h_u	upper layer depth (m)
h_{int}	interface thickness (m)
H	total stratification depth ($=h_l + h_{int} + h_u$) (m)
L_{int}	size of interrogation area (m)
l'	horizontal turbulent length scale (m)
M	grid mesh size (m)
Nu	Nusselt number
Pe	Peclet number
S	salt concentration (g of salt per 100 g solution) (%)
s	grid oscillation stroke (m)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (°C, K)
t	time (s)
R	spatial autocorrelation function
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
R_ρ	interfacial stability ratio
U	horizontal mean velocity ($m\,s^{-1}$)
u_e	entrainment velocity ($m\,s^{-1}$)
u	fluctuating horizontal velocity ($m\,s^{-1}$)
u'	horizontal rms velocity ($m\,s^{-1}$)
V	vertical mean velocity ($m\,s^{-1}$)
v	fluctuating vertical velocity ($m\,s^{-1}$)
v'	vertical rms velocity ($m\,s^{-1}$)
z_g	distance from grids (m)
$\Delta\rho$	density difference between mixed layers ($kg\,m^{-3}$, $g\,cm^{-3}$)
ΔS	concentration difference between mixed layers (%)
ΔT	temperature difference between mixed layers (°C, K)

Greek symbols

α	thermal expansion coefficient $= -\frac{1}{\rho}(\frac{\partial\rho}{\partial T})_S$ (K^{-1})
β	mass expansion coefficient $= -\frac{1}{\rho}(\frac{\partial\rho}{\partial S})_T$
φ_{losses}	heat losses (W)
k_T	thermal molecular diffusivity ($m^2\,s^{-1}$)
k_S	salt diffusivity ($m^2\,s^{-1}$)
λ_{ins}	insulation thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$, $g\,cm^{-3}$)
ρ_0	density reference of the lower layer at T_0, S_0 ($kg\,m^{-3}$, $g\,cm^{-3}$)
$\langle\,\rangle_i$	average in the x-direction

initially homogeneous layers at some distance from a density interface [1,7–9].

Turbulence generated by grid oscillation is characterized by experimental parameters that enter directly into its generation. Thompson and Turner [2] measured the properties of this turbulence in a homogeneous fluid using a hot film. They showed that their statistical quantities, defined as the horizontal rms velocity u' and the turbulent integral length scale l', depend strongly on the overall experimental parameters: the oscillation frequency f, the stroke s of the grid, the distance z_g away from the grid and the shape of the grid. They found that, for a square-barred grid with $s = 10$ mm, u' depends linearly on the stirring frequency f and decays as the -1.5 power with vertical distance z_g from the centre of the grid midplane. They also found that the integral length scale l' increases linearly with distance z_g from the grid. Hopfinger and Tolly [10], defining a virtual origin z'_g at which $l' = 0$, proposed an empirical turbulence decay law of the form

$$\frac{u'}{f_s} = C_1\left(\frac{s}{M}\right)^{0.5}\left(\frac{z'}{M}\right)^{-1} \tag{1}$$

for $M/d = 5$, where M is the grid mesh size and d is the bar size. The experimental constant was equal to 0.25 for a stroke s ranging from 40 to 90 mm. Ura et al. [11] give the same relationship with $C_1 = 0.19$ in the range $z_g/M \leqslant 5$. This form of the equation is widely used because of its simplicity.

Turner [12] measured the mixing rate across a density interface between two layers of liquid where the density difference across the interface is produced by heat or salt and the stirring is generated in one or both layers. His results suggest that the mixing rate across a density interface depends on the competition between inertial forces due to turbulence and the potential energy of the stratification defined through the overall Richardson number

$$Ri = g\frac{\Delta\rho}{\rho}\frac{l'}{u'^2} \tag{2}$$