DOUBLE DIFFUSIVE CONVECTION BETWEEN TWO PARALLEL PLATES WITH DIFFERENT BOUNDARY CONDITIONS

Yantao Yang[1], Erwin P. van der Poel[1], Rodolfo Ostilla-Mónico[1],
Chao Sun[1], Roberto Verzicco[1,2], Siegfried Grossmann[3] & Detlef Lohse[1]
[1]*Physics of Fluids Group, Faculty of Science and Technology, MESA+ Research Institute, and J. M. Burgers Centre for Fluid Dynamics, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands.*
[2]*Dipartimento di Ingegneria Industriale, University of Rome "Tor Vergata", Via del Politecnico 1, Roma 00133, Italy*
[3]*Fachbereich Physik, Philipps-Universität Marburg, Renthof 6, D-35032 Marburg, Germany*

Abstract We investigate the double diffusive convection between two parallel plates with either no-slip or free-slip boundary conditions. Direct numerical simulations have been conducted systematically for a series of control parameters. Salt fingers can be observed for both boundary conditions and all parameters explored. Compared to the no-slip case, salt fingers are stronger in the free-slip case, which is accompanied by larger salinity flux and flow velocity. For both boundary conditions, thin boundary regions develop adjacent to the two plates. The salinity flux and the Reynolds number show similar dependences on the control parameter, namely, the Rayleigh number of the salinity field.

INTRODUCTION

Double diffusive convection (DDC) refers to the buoyancy-driven convection flow where the fluid density depends on two components with very different molecular diffusivity. DDC is very important and common in oceanic mixing [9, 7]. In the ocean the fluid density is determined mainly by temperature and salinity. When salty and warm water locates above fresh and cold water, salt fingers can develop with very long vertical length and very small horizontal width [8]. Recently, Hage and Tilgner ([5], HT hereafter) conducted a series of experiments on DDC bounded by two parallel plates, and salt fingers were observed for their control parameters.

In HT experiments, the plates are no-slip boundaries with constant temperature and salinity. Here we would like to investigate the effects of two different boundary conditions in the DDC flow. Since in the ocean DDC often occurs away from the sea surface and floor, the free-slip boundary is closer to the realistic situation. The current study can then provide important insights to connect the experimental results to the oceanic applications. Moreover, the effects of no-slip and free-slip boundary conditions have been explored for Rayleigh-Bénard (RB) flow [6]. Such a study for DDC will also improve our understanding on buoyancy-driven flow.

FLOW FIELD

We carried out Direct Numerical Simulations (DNS) of the DDC flow. The flow domain is bounded by two parallel plates which are perpendicular to the direction of gravity. Our setup resembles that of HT experiments. At two plates either no-slip or free-slip boundary conditions are applied, and both the temperature T and salinity S are constant. The top plate always has higher T and S, so that the flow is constrained in the finger regime. We employed the Oberbeck-Boussinesq approximation. That is, the fluid density depends linearly on the two scalar fields. The Prandtl numbers of T and S are fixed at $Pr_T = 7$ and $Pr_S = 700$, which are the typical values of seawater. The other two parameters are the Rayleigh numbers Ra_T and Ra_S, which measure the magnitudes of the temperature and salinity differences between the two plates, respectively. For the details of the numerics, please refer to Ref. [10].

In Figs. 1(a) and 1(b) we illustrate the typical flow structures, i.e. the salt fingers, for two different boundary conditions. The colormaps are set to be the same. Clearly, the salt fingers are much stronger in the free-slip case. For instance, at the bulk region the salt fingers from the top plates have larger salinity in the free-slip case than those in the no-slip case. Figs. 1(c) and 1(d) plot the vertical profiles of the standard deviations of the salinity and vertical velocity. These two quantities are larger in the free-slip case than the no-slip case, implying again that the free-slip boundary allows stronger salt fingers to develop. Another interesting fact is that for both boundary conditions, thin boundary regions emerge adjacent to the two plates.

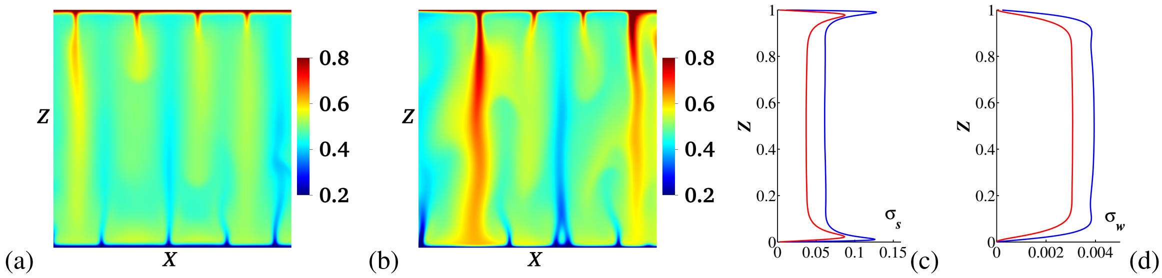

Figure 1. Contours of salinity field at $Ra_T = 10^6$ and $Ra_S = 5 \times 10^7$ for (a) the no-slip case and (b) the free-slip case. The vertical profiles of the standard deviations of (c) salinity and (d) vertical velocity. Blue line: the free-slip case, and red line: the no-slip case.

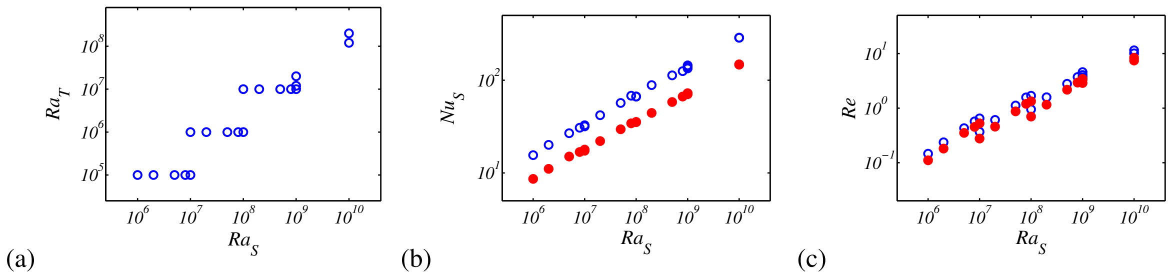

Figure 2. (a) The parameters explored in our DNS. (b) The dependence of Nu_S on Ra_S. (c) The dependence of Re on Ra_S. In (b) and (c), the blue open circles mark the free-slip cases and the red close circles mark the no-slip cases.

SYSTEM RESPONSES

The two important system responses are the salinity flux and the flow velocity, which are measured by the Nusselt number Nu_S and the Reynolds number Re based on the root-mean-square value of velocity, respectively. We systematically changed Ra_T and Ra_S in our DNS. The parameters explored are shown in Fig. 2(a). In Figs. 2(b) and 2(c) we show the dependences of Nu_s and Re on Ra_S. Both Nu_s and Re are larger in the free-slip cases, which is consistent with the fact that the free-slip cases have stronger salt fingers. For the parameters considered here, Nu_S in the free-slip cases are almost twice the values in the no-slip cases.

Finally, our numerical results suggest that the dependences of the salinity transfer and the Reynolds number on the salinity difference exhibit similar scaling laws for the two different boundary conditions. Meanwhile, the flow visualisations indicate that despite the boundary conditions, the flow domain always consists of a bulk region and two boundary regions. For Rayleigh-Bénard (RB) flow, this flow domain decomposition is the key idea for the development of the Grossmann-Lohse (GL) theory [1-4]. We have successfully applied the GL theory to DDC with the no-slip boundary condition [10]. The present results strongly imply that based on the GL theory, a uniform interpolation may be developed for DDC flow with either no-slip or free-slip boundary conditions.

References

[1] S. Grossmann and D. Lohse. Scaling in thermal convection: a unifying theory. *Journal of Fluid Mechanics*, **407**:27–56, 2000.
[2] S. Grossmann and D. Lohse. Thermal convection for large Prandtl numbers. *Physical Review Letters*, **86**(15):3316–3319, 2001. PRL.
[3] S. Grossmann and D. Lohse. Prandtl and Rayleigh number dependence of the Reynolds number in turbulent thermal convection. *Physical Review E*, **66**(1):016305, 2002. PRE.
[4] S. Grossmann and D. Lohse. Fluctuations in turbulent Rayleigh-Bénard convection: The role of plumes. *Physics of Fluids*, **16**(12):4462–4472, 2004.
[5] E. Hage and A. Tilgner. High Rayleigh number convection with double diffusive fingers. *Physics of Fluids*, **22**(7):076603, 2010.
[6] K. Petschel, S. Stellmach, M. Wilczek, J. Lülff, and U. Hansen. Dissipation layers in rayleigh-bénard convection: A unifying view. *Phys. Rev. Lett.*, **110**:114502, 2013.
[7] R.W. Schmitt. Double diffusion in oceanography. *Annu. Rev. Fluid Mech.*, **26**:255–285, 1994.
[8] M. E. Stern. The "salt-fountain" and thermohaline convection. *Tellus*, **12**(2):172–175, 1960.
[9] J.S. Turner. Double-diffusive phenomena. *Annu. Rev. Fluid Mech.*, **6**:37–57, 1974.
[10] Y. Yang, E.P. van der Poel, R. Ostilla-Mónico, R. Verzicco C. Sun, S. Grossmann, and D. Lohse. Salinity transfer in bounded double diffusive convection. *J. Fluid Mech.*, **Under review**, 2015.