Chemical Engineering Science 158 (2017) 245–256

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

The role of viscosity contrast on plume structure in laboratory modeling of mantle convection

Vivek N. Prakash[a,1], K.R. Sreenivas[a,*], Jaywant H. Arakeri[b]

[a] Engineering Mechanics Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur P.O., Bangalore 560064, India
[b] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

ARTICLE INFO

Keywords:
Mantle convection
Viscosity contrast
Rayleigh–Taylor instability
Plume dynamics

ABSTRACT

We have conducted laboratory experiments to model important aspects of plumes in mantle convection. We focus on the role of the viscosity ratio U (between the ambient fluid and the plume fluid) in determining the plume structure and dynamics. We build on previous studies to highlight the role of viscosity contrast in determining the morphology of mantle plumes and provide detailed visualizations and quantitative information on the convection phenomenon. In our experiments, we are able to capture geophysical convection regimes relevant to mantle convection both for hot spots (when $U > 1$) and plate-subduction (when $U < 1$) regimes. The planar laser induced fluorescence (PLIF) technique is used for flow visualization and characterizing the plume structures. The convection is driven by compositional buoyancy generated by the perfusion of lighter fluid across a permeable mesh and the viscosity ratio U is systematically varied over a range from 1/300 to 2500. The planform, near the bottom boundary for U=1, exhibits a well-known dendritic line plume structure. As the value of U is increased, a progressive morphological transition is observed from the dendritic-plume structure to discrete spherical plumes, accompanied with thickening of the plumes and an increase in the plume spacing. In the vertical section, mushroom-shaped plume heads at U=1 change into intermittent spherical-blob shaped plumes at high U, resembling mantle plume hot spots in mantle convection. In contrast, for low values of U (1/300), the regime corresponds to subduction of plates in the mantle. In this regime, we observe for the first time that plumes arise from a thick boundary with cellular structure and develop into sheet-plumes. We use experimental data to quantify these morphological changes and mixing dynamics of the plumes at different regimes of U. We also compare our observations on plume spacing with various models reported in the literature by varying the viscosity ratio and the buoyancy flux.

1. Introduction

The study of convection is important, with various parametric regimes of convection being relevant in different fields, for example, high Rayleigh number convection is important both in natural processes (e.g. atmospheric and mantle convection) and in engineering applications (e.g. chemical engineering industry and metallurgy) and has been studied extensively (Ahlers et al., 2009). Mantle convection occurs at moderately high Rayleigh and Prandtl numbers ($Ra \approx 10^6$ to 10^8 and $\mathrm{Pr} \approx 10^{24}$) in a configuration similar to Rayleigh-Benard Convection. Mantle convection in the earth is an important process by which heat is transported from the core to the surface and is responsible for volcanism, plate tectonics and orography (see reviews: Humphreys and Schmandt, 2011; Ribe et al., 2007; Jellinek and Manga, 2004). Morgan (1971) put forward the hypothesis that 'mantle plumes' are responsible for the origin of 'hotspots' on the earth. Mantle plumes detach from the thermal boundary layer (being lighter and less viscous due to higher temperature) at the core-mantle boundary and rise in a more viscous ambient mantle. These mantle plumes are difficult to observe and available information about them is based on indirect geological measurements (Zhao, 2001), and analog laboratory experiments like ours and numerical simulations (Kellogg and King, 1997; van Keken, 1997). The mantle primarily consists of solid silicate rock which can be regarded to behave as a fluid at geological timescales with a high viscosity $\approx 10^{18}\ \mathrm{m^2\ s^{-1}}$. Unlike Rayleigh-Benard convection, in mantle convection there are large variations in viscosity, pressure and composition. Capturing all these parameters in a single experiment is a challenge. The viscosity of the mantle is dependent on the composition, pressure and temperature (Schubert et al., 2001). A temperature increase of 100–300 °C can reduce the viscosity of the

* Corresponding author.
E-mail address: krs@jncasr.ac.in (K.R. Sreenivas).
[1] Present address: Department of Bioengineering, Stanford University, California, USA.

http://dx.doi.org/10.1016/j.ces.2016.10.012
Received 29 April 2016; Received in revised form 13 September 2016; Accepted 14 October 2016
Available online 18 October 2016
0009-2509/

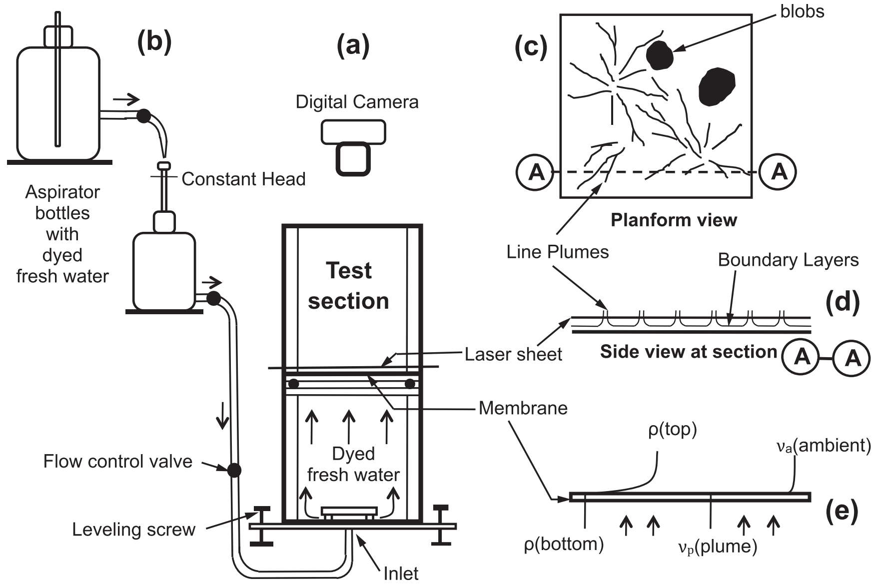

Fig. 1. Schematic of the experimental setup, (a) main experimental setup with test-section and digital camera, (b) constant flow-rate arrangement, (c) typical planform view of the plume structure just above the mesh, obtained by passing a horizontal laser-sheet above the mesh and dyed fluid from the lower chamber, (d) arrangement in the vertical section (side-view) and (e) density and viscosity profiles across the mesh.

mantle by a factor of 100–1000 (see Davies, 1999). Similarly, subduction - a geological process in which one edge of crustal plate is forced below its neighboring crustal plate, and its initiation and sustainability is also a topic of recent studies (Ueda et al., 2008; Sizova et al., 2010; Regenauer-Lieb and Yuen, 2000; Solomatov, 2004; Schubert et al., 2001). Subduction induced by cooler, heavier oceanic crust that plunges into the mantle (Ueda et al., 2008; Sizova et al., 2010), corresponds to the situation where a more viscous plume is moving into low viscosity mantle driven by a density difference. Thus, the prime factors that set apart mantle convection are the extremely high value of Prandtl number and high viscosity contrast between plumes and the ambient fluid. These two factors play a crucial role in determining the plume longevity, mixing, rise velocities and hence, the heat transfer within the mantle (Olson and Singer, 1985; van Keken, 1997; Lenardic and Jellinek, 2009).

In this work, we investigate the role of viscosity ratio U (viscosity of ambient fluid/viscosity of plume fluid) on the structure and dynamics of plumes. In our experiments, we have used compositional buoyancy to drive the convective flow. In this study, we are concerned with the effect of the viscosity ratio, U, on the (a) spacing and morphology of plumes, (b) structure and dynamics of the rising plumes and (c) longevity and mixing of plume with the ambient fluid.

In previous convection experiments driven by thermal buoyancy for example (Manga and Weeraratne, 1999; Lithgow-Bertelloni et al., 2001), the buoyancy flux and fluid viscosity were coupled as the fluids had a temperature-dependent viscosity. The use of compositional buoyancy to drive the convection provides us the opportunity to study independently the effect of viscosity contrast on the plume structure decoupled from other parameters. Compositional buoyancy has been used to study plumes rising from point sources at different viscosity ratios (Whitehead and Luther, 1975; Olson and Singer, 1985). These studies have led to the standard accepted model of a mantle plume: a large, bulbous head trailed by a narrow conduit or tail connecting it with its source. In the present study, plumes arise as boundary layer instabilities from the bottom surface, driven by compositional buoyancy. The fluid dynamical regime corresponds to something in between the flow associated with a Rayleigh–Taylor instability and Rayleigh-Benard convection. Previous experiments on convection across a mesh, have reported different regimes depending on the magnitude of the concentration differences across the mesh, a diffusive regime (Puthenveettil and Arakeri, 2005) similar to Rayleigh-Benard convection, and an advection regime (Puthenveettil and Arakeri, 2008) with the existence of a through flow across the mesh. In our experiments, we externally impose a through flow across the mesh, and the advection velocities are ~0.083 cm s^{-1} (at least 10 times greater than the previous work by Puthenveettil and Arakeri (2008)). The experiments of Jellinek et al. (1999) used a similar setup but their primary motivation was to study mixing in different viscosity ratio regimes ($U \approx 1/850$ to 20,100).

Our focus is to study the effect of U on plume structure and plume dynamics by flow visualization experiments. We report results on the planform plume structures and quantify the changes in plume morphology, plume dynamics and the plume mixing effectiveness over a wide range of viscosity ratios ($U \approx 1/300$ to 2500) using image processing. Here, since we have used concentration differences to provide compositional buoyancy, the Schmidt number (Sc) is a proxy to the Prandtl number. In our experiments, we are able to simultaneously achieve high Rayleigh numbers $\approx 10^{11}$ and high Schmidt numbers $\approx 10^{6}$.

In addition to mantle convection, this work is also of interest to chemical engineers because the viscosity contrast as a parameter is relevant in the chemical process industry, e.g. in blending of additives into polymer melts. The new mixing effectiveness measure we propose here provides a useful and stringent tool to quantify mixing in a variety of industrial contexts, e.g. in batch versus continuous mixing in various chemical processes.

In Section 2, we present details of the experimental setup and the methodology, followed by the results in Section 3 with flow visualization pictures of plume structures showing the dependence of the convection pattern and dynamics on the viscosity ratio U, Ra and Sc numbers with a constant buoyancy flux. We also report preliminary results on the effect of varying the buoyancy flux while U is held constant. In the concluding Section 4, we summarize the results from the present study.

2. Experimental set up and methodology

A schematic of the overall experimental setup and visualization process is shown in Fig. 1. The experiments have been conducted in a square cross-section tank that is divided into two chambers by a permeable mesh. The convection is driven by a concentration difference across the mesh with heavier sugar solution in the upper chamber and lighter fresh water in the bottom chamber. The test section is the upper chamber of the tank which has a 15.5 cm×15.5 cm cross-section