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Real-time two-color interferometric technique for simultaneous measurements of temperature and solutal fields

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ABSTRACT

Development of a real-time Mach–Zehnder based dual wavelength interferometry technique for studying the double-diffusive convection phenomena is presented. The interferometer employs two different monochromatic light sources with wavelengths of $\lambda_1 = 632.8$ nm and $\lambda_2 = 457.9$ nm. A high resolution color CCD sensor has been employed to record the interferograms that carry phase information pertaining to the coupled effects of the two wavelengths used. Phenomenon of double-diffusive convection has been set up in a two-layered salt-stratified solution that is destabilized by isothermal heating at the bottom wall of the test cell. The resultant changes in the thermal and solutal fields have been simultaneously captured using the developed interferometric technique. Experiments have been performed at a stability ratio of $R_\rho = 1.02$ and thermal Rayleigh number of $Ra_T = 6.0 \times 10^5$. The work presents a detailed methodology for quantitative determination of temperature and/or concentration fields from a single dual wavelength interferogram. Results have been presented in the form of dual color interferometric images and contours of whole-field temperature distribution as a function of experimental run time. The two-dimensional contours of concentration field at time instant $t = 0$ min have been presented. The observed variations in the fringe patterns are primarily due to thermal gradients prevailing in the fluid layer. In addition to the quantitative studies, interferometer also acts as a flow visualization tool and fringe patterns give qualitative insights into the flow field. The fringe patterns indicate towards the possibility of the existence of mechanical coupling between the two fluid layers wherein the direction of circulatory movement of fluids in each layer is oppositely oriented.

1. Introduction

Natural convection, one of the most widely studied phenomena, has unstable density distribution caused by temperature and/or solutal gradients. It has been shown by Turner and Stommel [1] that it is possible to have convection in systems having overall stable vertical density distribution with two components of different molecular diffusivities. This phenomena is to be generally observed e.g. in deep oceans with layers of uniform temperature and concentration, arranged in staircase like manner, separated by sharp density interfaces. The rate of transport is much higher than what molecular diffusion can account for and thus gives rise to a whole new range of phenomena. It has also been observed that similar phenomena do appear in several engineering problems of interests such as crystal growth processes [2,3], LNG containers [4–5], solar ponds [6], solidification [7–10] etc. and in natural systems such as magmas[11], celestial bodies [12] etc. In these systems, one component has stabilizing effect and the other one has destabilizing effect on the overall vertical density profile.

Turner [13] studied the transport of heat and salt across an interface in a cylindrical tank heated from below at various heat fluxes and it was found that ratio of fluxes of solute concentration and heat is a function of stability ratio R_ρ and the critical stability ratio is 2. At low stability ratios ($R_\rho < 2$), the relative transport of salt to heat is much higher compared to the transport of the same at high stability ratios. It has been shown by Okorafor et al. [14] that double-diffusive convection experiment performed with low stability ratio has active interfacial dynamics, lower mixing time and vice versa. Bergman et al. [15] studied double diffusive convection in a two layered salt stratified solution being destabilized by lateral thermal gradients. Tanny et al. [16] investigated the structure and instability characteristics of double-diffusive interface in two layered salt stratified medium with lateral thermal gradients.

Double-diffusive convection experiments in the diffusive regime have largely been performed in two different modes of heat and mass transfer; coupled heat and mass transfer processes

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taking place in the same (vertical) direction (bottom wall heating experiments) [17] and heat and mass transfer taking place in mutually perpendicular directions (side wall heating experiments) [18,19]. The available literature shows that little attention has been paid to the study of two-layered salt-stratified medium destabilized by isothermal heating from bottom which can help develop an understanding of the double-diffusive convection phenomena, a subject which is of interest in a range of applications e.g. aqueous solution-based crystal growth processes [20–22]. Initially, several researchers used a thermocouple-conductivity meter probe, which is intrusive in nature, to get temperature and concentration information but this approach limited their study to select number of points only and the whole field measurements of these parameters are not possible. Later on, researchers used other techniques such as schlieren, shadowgraph, liquid crystal thermography [23], polarigraphy [24] etc. However, these studies have primarily been qualitative in nature and also do not provide simultaneous information of temperature and concentration fields.

Double-diffusive convection systems are characterized by simultaneous presence of thermal and solutal fields and it is necessary to study the influence of both the fields in order to develop complete understanding of the phenomena. In this context, Lewis et al. [25] studied double diffusive convection in a linearly stratified medium heated from below using a single wavelength Mach–Zehnder interferometer to measure concentration distribution while temperature information at select points was obtained using thermocouples. The usage of thermocouples leads to physical intrusion into the system and also it precludes obtaining whole-field temperature data. In order to study the temperature and concentration fields simultaneously, dual wavelength interferometer has been proved to be a potential tool. Mehta [26] employed both dual as well as single wavelength interferometers to study double-diffusive convection in a linearly stratified salt solution. However, the interferometric study was not simultaneous as it involved sequential recording of the interferograms (time-lapsed images). Ecker [27] employed dual wavelength holographic interferometer to simultaneously study temperature and concentration fields during solidification of a transparent alloy system. Chen et al. [28] studied double-diffusive convection in a two-layered system destabilized by lateral heating and cooling using dual wavelength holographic interferometry. The authors investigated the temporal behavior of heat and mass transfer across the interface and the related interfacial dynamics. The disadvantage of using holographic interferometry lies in the fact that this technique requires various steps associated with the chemical processing of the holographic plates and hence one obtains time-lapsed experimental data.

The above-presented literature suggests that dual wavelength interferometry is an ideal technique, compared to its counterparts, for simultaneously studying the whole-field temperature and concentration fields in double-diffusive systems. Though quite a few attempts have earlier been made in applying this technique to study double-diffusive convection phenomena, these attempts have had the drawback of not recording the fringe patterns corresponding to the two wavelengths simultaneously. Effort have also been made to develop holographic interferometers, but considerable amount of time and efforts need to be spent for developing the holographic plates. Hence, it is of interest to develop a dual wavelength interferometer of the conventional Mach–Zehnder type which can record fringe patterns of different wavelengths using single sensor only.

With this background, we report the development of a two-color Mach–Zehnder interferometer and demonstrate its potential application for investigating the double-diffusive convection phenomena. The developed interferometer enables the recording of fringe patterns produced by two different wavelengths using a single CCD sensor in real time. The instrument offers non-intrusive, real-time study of whole-field temperature and concentration fields. The fringe patterns produced by two wavelengths have been recorded simultaneously using a single Bayer mosaic color CCD sensor with pixel size of 4.65 μm × 4.65 μm. Two colors i.e. red (λ_1 = 632.8 nm) and blue (λ_2 = 457.9 nm) have been employed and the images pertaining to these two colors have been stored in their corresponding color channels. This allows the segregation of the information related to the two colors. Experiments have been performed in infinite fringe setting mode of the interferometer. Appropriate data analysis methodology has been developed and presented. The experiments have been performed in a two-layered salt-stratified solution with an initial temperature step of ΔT_i = 11.5 °C and an initial concentration step of ΔC_i = 0.4 (wt/wt)%. This configuration corresponds to an initial stability ratio of $R_{\rho,i}$ = 1.02 and initial thermal Rayleigh number of $Ra_{T,i} = 6 \times 10^5$. Temporal behavior of temperature and concentration fields in the two layered double-diffusive convection system that is destabilized by heating from the bottom horizontal surface has been presented and discussed.

2. Apparatus and instrumentation

The experiments reported in the present work have been performed in a test cell made of high quality quartz material (Flatness: $\lambda/6$ and with a total transmittance of ≈ 85% for the wavelengths employed in the experiments) to ensure undisturbed passage of the laser beam. The schematic diagram of the test section has been shown in Fig. 1(a). The interior walls of the cell measure 30 × 30 × 30 mm with a wall thickness of 2.5 mm. Constant temperature conditions at the bottom wall of the cavity have been realized by placing it on a water circulation bath made up of copper. A sufficient number of baffles have been provided to ensure circuitous flow pattern of pre-thermostated water from a constant temperature water bath (*Raaga Industries*) with a temperature uniformity of ±0.1 °C. In order to circumvent the problem of air pockets between the test cell and the top surface of copper bath, a thermal conduction slab made up of silicone (*thermal conductivity*: 4.1 W/m-K) and silver based thermal paste (*thermal conductivity*: 8.7 W/m-K) have been sandwiched in this space. The photographic image of the experimental setup is shown in Fig. 1(b). Sufficient insulation (4.5 cm thick Styrofoam sheet) has been provided around the test section in order to ensure minimum effects of external thermal fluctuations.

Projection data of the refractive index variations caused due to the coupled effects of temperature and concentration have been recorded in the form of interferograms using the developed interferometer.[1] The schematic diagram of dual-wavelength Mach-Zehnder interferometer has been shown in Fig. 2(a). As shown, two separate lasers (λ_1 = 632.8 nm, cw He–Ne laser with a power output of 30 mW and λ_2 = 457.9 nm, cw Ar-ion laser, 8 mW) have been employed as the light sources. The two laser beams have first been multiplexed using a 50 mm cubic beam splitter and the multiplexed beam has then been collimated to give a dual-color parallel

[1] In view of the fact that a Mach–Zehnder interferometer provides projection data of temperature and/or concentration field (integrated along the direction of the propagating laser beam), the results presented in this manuscript are two-dimensional in nature. However, this limitation may be overcome by recording the projection data from different view angles (e.g. 0, 45, 90 and 135°) and subsequently applying the principles of tomography for the reconstruction of complete three-dimensional information about the field of interest [29,30]. In view of the fact that the present manuscript primarily focuses on the development and demonstration of real time two-color interferometric technique, tomographic reconstructions are beyond the scope of the present work. The complete three-dimensional studies would be reported in our future communications. Experience of the authors of the present work with tomographic reconstructions can be seen elsewhere [20,31,32].