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On the influence of g-jitter and prevailing residual accelerations onboard International Space Station on a thermodiffusion experiment

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HIGHLIGHTS

- The influence of g-jitter on board ISS on heat and mass transfer.
- The CFD simulations using the real acceleration data recorded on board.
- The results of interval Root Mean Square is not realistic.
- Low-frequency g-jitter has stronger impact on diffusion process.
- G-jitter on board ISS under nominal condition does not affect the Soret separation.

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ABSTRACT

The influence of g-jitter onboard the International Space Station (ISS), on diffusion in liquids and more specifically on thermodiffusion experiments has been a controversial issue. Meanwhile, only a few studies have implemented real acceleration data recorded during a specific experiment. This study, numerically surveys a typical thermodiffusion experiment that has been performed on ISS in late 2009 (IVIDIL-Run2). The simulations employed the real acceleration data recorded in the same time for both residual (quasi-steady) and g-jitter accelerations. Different interval methods have been applied to extract the data from g-jitter for the fluid dynamic simulations. It was obtained that the results of interval Root Mean Square (RMS) is not realistic. Furthermore, the current study suggests a relation with the low-frequency contribution of the g-jitter and the deviations in the separation process throughout the experiment. It was obtained that low-frequency contribution of g-jitter is most-likely responsible for disturbing ideal diffusion process.

1. Introduction

Thermodiffusion or the Soret effect is the tendency of components in a mixture to separate under the influence of a local temperature gradient. Thermodiffusion inherently is a slow-process which is governed by diffusion. With certain applications in mass transfer in the oil and mineral industry [1], this phenomenon has also been a subject of microgravity science recently.

One of the major concerns of the thermodiffusion research is to obtain the thermodiffusion coefficient or the Soret coefficient for the mixtures. Due to smallness of the involved mass fluxes, absolutely "undisturbed" experimental conditions are needed for a thermodiffusion experiments. The accuracy of the experiments can be highly affected by buoyancy-induced flows (due to natural convection). Space platforms such as the International Space Station; provide a unique opportunity to perform fluid science with minimizing the buoyancy flows [2]. Using the latest technologies thermodiffusion experiments have been conducting in space platforms benefiting from the reduced gravity environment [3,4]. Nevertheless, the unavoidable micro-accelerations prevailing on space platforms are still a source of error. These accelerations known as g-jitter may cause due to crew activity, thruster firing, docking/berthing of the spacecraft, and micrometeorite impacts. There have been numerous numerical studies discussing the effects of g-jitter on fluid flow experiments. In fact numerical simulations have the potential advantage of being less expensive and often provide the only means to understand g-jitter effects.

Alexander [5] carried out a numerical investigation on the effect of g-jitter on dopant concentration in a modelled crystal-growth reactor. He concluded that low-frequency g-jitter can have a significant effect on dopant concentration.

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Monti and Savino et al. [6–9] studied thermophysical experiments in typical microgravity conditions. Using a time-averaged method they investigated the disturbing effects of g-jitter vibrations by considering the quasi-steady residual-g and single frequency oscillations. They have shown that error in the experiments may arise for residual-g on the order of μg as well as for extremely large g-jitter.

Many other studies have simplified the g-jitter vibration into a single-frequency sinusoidal signal [10,11]. The common outcome of all those surveys was the fact that the diffusion process is rather to be affected by the low-frequency gravity fields. Moreover, the effect of amplitude of the vibrational gravity field is also important. Larger accelerations results in stronger induced flow and convection inside the cell restricting the separation of species due to the Soret effect.

Few other researchers used the raw acceleration data onboard space platforms which were recorded during the experiments. Shu et al. [12] have considered idealized single-frequency and multi-frequency g-jitter as well as real g-jitter data taken during an actual space shuttle flight. Their numerical study indicates that with an increase in g-jitter force (amplitude), the nonlinear convective effects become more pronounced which in turn drastically changes the concentration fields.

Srinivasan et al. [13] performed a CFD investigation on a ternary hydrocarbon mixture of methane, n-butane, and n-dodecane subjected to the micro-acceleration microgravity environment of the FOTON-M3 spacecraft. Due to their methodology for extracting acceleration data from raw measurements, all the applied accelerations were positive in sign. This resulted in formation of a single convection cell in the domain. It was shown that the effect of micro-vibration on FOTON M3 is insignificant.

More recently, Ahadi and Saghir [14] performed a numerical study on the effect of g-jitter vibrations on thermodiffusion experiments for two space platforms: ISS and FOTON. They have studied water/IPA (Isopropanol) mixtures (50%wt or 90%wt water). The actual acceleration data (measured onboard the platforms) were used. They considered the Root Mean Square (RMS) value of the recorded acceleration within time intervals equal to the simulations' time step. For case of FOTON spacecraft, they used high-order interpolation to provide acceleration data for CFD analysis. Their results show relatively significant effect of g-jitter vibrations on the thermodiffusion. The mixing effect is considerable when the RMS values of g-jitter were applied. For the case of FOTON, it was concluded that the environment is more suitable for performing such experiments. Ahadi and Saghir [14] also investigated the role of cavity size.

In October 2009, an interesting experimental study performed in the ISS named IVIDIL (Influence of Vibration in Diffusion in Liquids) [3]. In total, 55 experimental runs (41 original and 14 reruns) were conducted. The first 26 runs were devoted to the mixture of 10% IPA and 90% water, a mixture which has a negative Soret coefficient. In each run the experimental cell is subjected to a temperature gradient to trigger the Soret effect while vibrating harmonically. The variation of concentration of the species in the domain is recorded using interferometry technique.

IVIDIL project has been insightful in understanding the complex process of thermal diffusion in the presence of controlled vibrations. Some of the results of this project have been published [15,16] while detailed study of the IVIDIL project is still in progress [17].

Some of the experimental results of IVIDIL project have been presented by Shevtsova et al. [15]. They have briefly reported the results of six experiments which were performed in the natural environment of the ISS (without force vibration). Results were extracted using image processing techniques for water/IPA mixtures with either 90% or 50% mass percentages of water. The results show great reproducibility of the experiments which were in noticeable agreement with numerical calculations of ideal (zero gravity) case for the 90% water mixture. The time lag between the two similar experiments (Run2 and Run2R) was considerably large and the authors claimed limited influence of g-jitter during the ISS normal operating condition [28,30].

Kianian et al. [16] also published the results of IVIDIL project for 4 runs of Water–Isopropanol mixture (90% of water). This detailed study presents the evolution of the separation in the experimental cell. The results show that the external forced vibration affects the separation process by increasing the vibrational Rayleigh number. For case of Run2, which is performed in pure microgravity environment (no external vibration applied), there is a good agreement with the benchmark outcomes indicating the suitability of the microgravity environment. However, in the separation curve local fluctuations and deviations are observed which might be related to the prevailing micro-acceleration onboard ISS.

The main motivation of this work is to investigate the relation between the prevailing acceleration onboard ISS and the local fluctuations in the separation curves. This study is also meant to investigate the sensitivity of the experiment to different micro-acceleration regimes onboard ISS. This study, implements the real acceleration data recorded during the same period of IVIDIL Run2. Both the effect of quasi-steady and g-jitter accelerations using different methodology and frequency contribution range is studied.

2. Computational domain and governing equations

The computational domain consists of a 1 cm by 1 cm square (similar to the experimental cell of IVIDIL). The top and bottom sides are kept in constant temperature providing a certain temperature difference (ΔT). The gravitational acceleration has been considered in both x and y directions. The acceleration data adopted from the real recorded data and are provided for each time step in both directions.

The problem is governed by the conservation of mass, momentum, energy and species equations as are described respectively in below:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\frac{D\vec{V}}{Dt} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{V} + \vec{g} \tag{2}$$

$$\frac{DT}{Dt} = \frac{k}{\rho c_p}\nabla^2 T \tag{3}$$

$$\frac{Dc}{Dt} = D_c \nabla^2 c + D_T c_0 (1 - c_0) \nabla^2 T \tag{4}$$

where the operator $D/Dt = \partial/\partial t + u\partial/\partial x + v\partial/\partial y$; ρ is the density; T is the temperature; c is the mass concentration of water; c_0 is the initial concentration of the water (0.9); p is the pressure; $\vec{V}$ is the velocity vector, c_p is the specific heat; k is the thermal conductivity; υ is the kinematic viscosity; $\vec{g}$ is the gravity vector; D_c and D_T are the molecular diffusion and thermodiffusion coefficient respectively. The Soret coefficient is defined as the ratio of molecular diffusion on the thermodiffusion coefficient.

$$\boldsymbol{S_T} = \frac{D_T}{D_c} \tag{5}$$

Due to the small variation of temperature and pressure in the simulations all of thermodynamic properties where assumed to be