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# Experimental study of the impacts of forced vibration on thermodiffusion phenomenon in microgravity environment

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## HIGHLIGHTS

- Increase in Gershuni number causes decrement in the separation.
- Various patterns of separation versus time observed for different vibrations.
- Optical temperature measurement must be considered in MZI thermodiffusion experiment.
- At high *Gs*, maximum separation does not occur at the end of thermodiffusion phase.
- The time that maximum separation occurs decreases as vibration level increases.

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## ABSTRACT

The SODI-IVIDIL (Selectable Optical Diagnostics Instrument-Influence of Vibrations on Diffusion of Liquids) project was performed on board the International Space Station to study the possible influences of a wide range of forced vibration on thermodiffusion measurements in a condition of microgravity subjected to three temperature differences. In this study, the effects on a thermodiffusion experiment of increasing the Gershuni number ($Gs$) from zero to $Gs \sim 3 \times 10^3$ with a constant temperature gradient of 15 K were studied for the first time. While many investigations have been done studying thermodiffusion phenomena in a microgravity condition, and preliminary discussions on IVIDIL objectives have been proposed, only a few works can be found in the literature that address the result of this project. ISS experimental results were obtained that were based on optical digital interferometry in a reduced gravity environment. Nine runs of water and isopropanol with a negative Soret coefficient and a temperature difference of 15 K were analyzed as test cases in this study. However, results indicate a maximum separation and Soret coefficient for the case with a minimum Gershuni number, and different concentration profiles and separation patterns were observed. Remarkably, when $Gs = 1.5 \times 10^3$, the maximum separation may not occur at the end of diffusion time.

## 1. Introduction

Due to localized temperature differences, the movement of the components of a mixture to either hot or cold areas without convection is known as thermodiffusion [1]. Based on different application of this phenomenon, it can be called thermal diffusion, the Ludwig–Soret effect, or the Soret effect [2–4]. The ratio of the thermodiffusion coefficient over diffusion coefficient is known as Soret coefficient ($S_T$). Thermodiffusion is caused by the diffusive coupling between heat and mass transports. The combination of two phenomena, convection and thermodiffusion, is called thermogravitational diffusion [2]. The Soret coefficient is recognized to be difficult to determine because of technical constraints in the control of liquid convection and convective instabilities due to gravity [5–7]. However, measurements conducted in a controlled microgravity environment minimize the perturbation effects of gravity and allow the true diffusion limit to be achieved. A microgravity environment provides suitable environment for studying the behavior of liquids and measuring the transport coefficients.

Different sources such as experiment operation, aerodynamic drag, gravity gradient, life-support systems, equipment operation, crew activities, and rotational effects create microgravity vibration on-board vehicles in microgravity environments [5,8,9]. This microgravity vibration is one of the most important factors that can affect thermodiffusion experiments on board the ISS. Other factors can be caused by optical setup, measurements and analysis errors. It has been argued that controlled vibrations or g-jitter vibrations in

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**Nomenclature**

| | |
|---|---|
| $\Delta n$ | change in refractive index |
| $\Delta C$ | maximum concentration difference |
| $A$ | vibration amplitude [mm] |
| $i,j$ | coordinate index of pixel |
| $f$ | vibration frequency [Hz] |
| $x,y$ | coordinate system |
| $u,v$ | Fourier transform of coordinate |
| $Gs$ | Gershuni number |
| $Nu$ | Nusselt number |
| $c_o$ | initial concentration |
| $D$ | molecular diffusion coefficient [m$^2$/s] |
| $D_T$ | thermodiffusion coefficient [m$^2$/K/s] |
| $m,n$ | number of pixels in $x$, $y$ direction |
| $L$ | optical length of the cell [mm] |
| $\Delta\phi$ | phase distribution |
| $S_T$ | Soret coefficient [1/K] |
| $\Delta T$ | temperature difference [K] |
| $t$ | time [s] |

*Greek symbol*

| | |
|---|---|
| $\omega$ | angular velocity [rad/s] |
| $\rho$ | density [kg/m$^3$] |
| ω | angular frequency [rad/s] |
| $\lambda$ | laser wavelength [nm] |
| $\mu$ | mixture viscosity [mPa s] |
| $\tau$ | relaxation time [s] |
| $\chi$ | thermal diffusivity [m$^2$/s] |
| $\beta_T$ | thermal expansion coefficient [1/K] |
| $\beta_C$ | concentration expansion coefficient [1/K] |
| $\nu$ | viscosity [m$^2$/s] |
| $(\partial n/\partial T)_{p,c}$ | temperature contrast factor [1/K] |
| $(\partial n/\partial C)_{p,T}$ | concentration contrast factor [−] |

*Subscript and abbreviation*

| | |
|---|---|
| CCD | charge coupled device |
| *exp* | experimental |
| h | hour |
| min | minute |
| MZI | Mach–Zehnder interferometry |
| ISS | International Space Station |
| IVIDIL | Influence of Vibrations on Diffusion of Liquids |
| *ref* | reference |
| *th* | thermal |
| *St* | steady |
| *os* | oscillatory |
| SODI | Selectable Optical Diagnostics Instrument |
| *vib* | vibration |

a reduced gravity condition can reduce the separation of components in a mixture [3,10–13]. For this reason, the SODI-IVIDIL[1] experiment investigated the effect of vibrations on thermodiffusion measurements.

The uncertainties of the SODI-IVIDIL[1] optical system have been discussed in different investigations. For instance, the effects of this vibration, which are recorded on board the ISS were studied in detail by Ahadi and Saghir [5] and Shevtsova et al. [14,15] and it was found that as soon as this system encounters microgravity perturbations that are greater than critical value, the experimental points start to deviate from the theoretical curve and exhibit larger scattering.

Because of the vibrations and non-uniform temperature field, specific flow patterns in the liquid appear. These flows are called thermovibrational convection, and are caused by differences in the inertias of cold and hot parts of the fluid with respect to the vibrational acceleration. These vibrational flows are characterized by the vibrational analogue of the Rayleigh number (Rayleigh vibration or Gershuni number) [5,13].

The direct numerical analysis of Srinivasan et al. showed that imposing ISS vibrations may change the Soret effect. They observed that a single convective flow cell is established. They claimed that such a cell is responsible for a mixing effect, destroying most of the Soret separation [16–18]. It was suggested that when the thermodiffusion experiment was performed under high levels of g-jitter vibration ($10^{-4}$ [m/s$^2$]) an underestimated value for $S_T$ was measured. In contrast, when ISS micro-vibration conditions were normal, pure thermodiffusion occurred, and as a result of which an accurate $S_T$ close to benchmark value was found [5]. It was shown by analyzing the g-jitter vibration during considered runs in the present study that the ISS provides a suitable condition for these thermodiffusion experiments.

Gershuni et al. performed a series of studies on the hydrodynamics and stability of fluid flow subjected to oscillatory gravity fields [19–22]. It was demonstrated that when vibration is applied, single or multiple cells flow is induced in the domain, which is harmonized according to the applied vibration. The velocity and mixing in the system disturbs the pure diffusion. Nevertheless, even in the presence of large induced velocities, thermodiffusion is not immediately affected by the convective motion of the fluid.

Shevtsova et al. have studied the effects of controlled vibration on a mixture by measuring different physical quantities [14,15,23–26]. Their investigations improved the understanding of the kinetic mechanisms that drive diffusion. The effects of g-jitter on molecular and thermal diffusion processes were discussed in detail. Shevtsova et al. not only presented the first results of the IVIDIL experiment conducted in the Glovebox in 2009–2010, but also shared experience on the procedures of communicating with the ISS environment [14,15,23,24,27,28].

The convection pattern in thermovibrational experiments in low gravity and in the presence of g-jiiter vibrations have been studied [9,26,29–31]. The transition from four-vortex flow to a pattern with three vortices was observed in the transient state. Furthermore, the convective flow induced by residual accelerations in a microgravity condition was studied by Ruiz et al. for different geometric arrangements [32]. In their study, both constant and oscillating accelerations were considered, and their focus was on the transient relaxation dynamics.

Finally, a brief summary of the state of the art in theoretical, experimental, and numerical approaches to studying thermodiffusion was presented [2]. The concepts and equations that provide the mass flux of constituents in binary, ternary, and multicomponent mixtures were presented. G-jitter leads to a non-zero mean flow, which may have an important effect on the average heat transfer in the system. High frequency vibrations can also significantly alter Earth bound experiments. In the case of experiments performed without gravity, only the specific thermovibrational mechanism was responsible for instabilities. It was concluded that vertical vibration has a stabilizing effect, while horizontal vibrations have a destabilizing effect on the onset of convection [2].

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[1] Selectable Optical Diagnostics Instrument-Influence of Vibrations on Diffusion of Liquids.