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The IVIDIL experiment onboard the ISS: Thermodiffusion in the presence of controlled vibrations

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ABSTRACT

The IVIDIL (Influence of VIbrations on DIffusion in Liquids) experiment was aimed at utilizing the International Space Station for investigating the effects of vibrations on liquid diffusion and thermodiffusion. The SODI-IVIDIL project of ESA is gathering together European, Canadian and Russian researchers with complementary skills to prepare and carry out the experiment, to process the raw data and perform numerical modeling of the phenomena. The experiment IVIDIL started on the October 5, 2009. In total 55 experimental runs were successfully completed by 20 January, 2010. A general description of the ISS facility related to the diffusion experiments and accessible for European researchers is briefly presented and some details about IVIDIL instrument are given. The scientific interest of this short article is focused on one of the objectives of the experiment: performing precise measurements of diffusion and thermodiffusion coefficients for binary mixtures in the absence of gravity. We demonstrate possibility of the experimental environment and report on the first results related to measurements of mass transport coefficients in the mixture with the negative Soret effect: 10% isopropanol (IPA)–90% water.

1. Introduction

When a mixture is subjected to a thermal or compositional gradient, the mass fluxes of the individual components appear. This process is referred to as molecular or thermodiffusion depending on the gradient that induces the fluxes. Although several theoretical approaches have been presented in the literature there is no unambiguous theory for thermodiffusion in liquids. A recent paper by Harstad [1] has presented comprehensive literature survey on theoretical description of the Soret effect in dense media.

The prediction of mass transfer in multi-component systems greatly relies on the knowledge of diffusion and thermodiffusion coefficients which should be measured. There exits only a few measurements of mass transport coefficients in ternary mixtures [2–4]. Consideration of multi-component systems, firstly, demands well established techniques for binary mixtures. A review by Wiegand [5] has discussed various experimental optical methods utilized in measurements of transport coefficients through 2003. The comparative analysis of actively used techniques for measurements of Soret coefficients was given by Platten [6].

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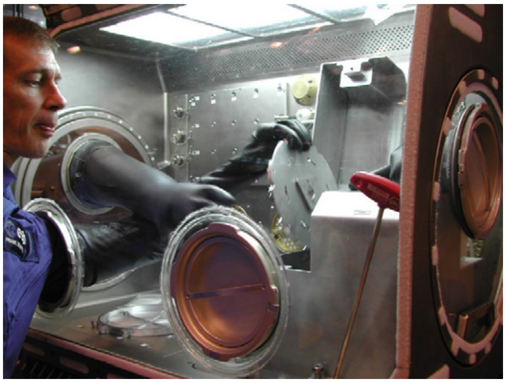


Fig. 1. Glovebox facility on the ISS in which diffusion experiments can be performed.

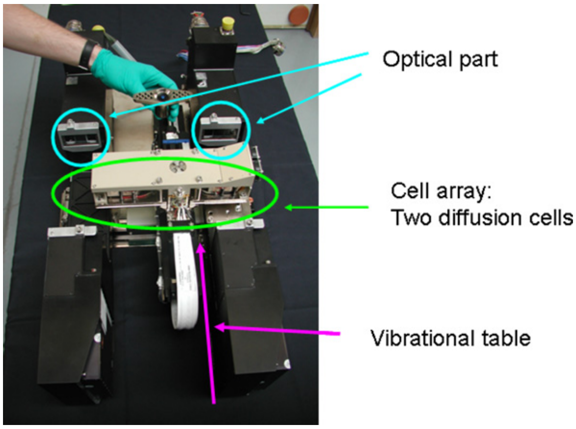


Fig. 2. Core part of IVIDIL instrument.

There is no universal technique that works for measuring the Soret coefficient of any binary mixture. Each technique has its own limitation. Besides, all experimental techniques require establishing a temperature gradient in the fluid in gravity field. This condition easily provokes convection in terrestrial conditions which disturbs or even erases component separation. The effect of convection is more pronounced in the case of negative Soret when the heavy liquid goes to the hot wall (against gravity). Note that convection can also appear in theoretically stable configurations due to the non-ideality of an experimental setup, which lead to unstable temperature (density) stratification.

The microgravity environment is a unique tool for studying the behavior of liquids and measurements of transport coefficients. However, in real space experiments, the benefit of the free fall condition may be altered by residual stochastic accelerations also known as g-jitter. Even if the overall forces caused by disturbances are relatively small (ranging from 10^{-2} to 10^{-6} times the normal gravity), the effect may be non-negligible for long duration experiments such as the ones that involve diffusion driven phenomena. One of the aims of the IVIDIL is to characterize the spectral influence of g-jitter.

Three International Teams were involved in the preparation of the experiment [7]. ULB, MRC team (led by V. Shevtsova) is responsible for coordination of the entire project, all aspects related to IVIDIL experimental definition and guidance of numerical modeling. Russian team from Perm, ICMM UB RAS (led by T. Lyubimova) and team from Ryerson University (led by Z. Saghir), Ontario, Canada provide theoretical and numerical support. The preparation of the experiment was outlined in [8]. The present paper aims to present a general description of the experiment IVIDIL, its performance on the ISS and the first preliminary results.

2. Experimental

2.1. Conducting the scientific experiment on the ISS

Equipment on the ISS is placed in autonomous boxes, which are fully sealed and completely isolated from the rest of the Station. Nevertheless they share the weightlessness and g-jitters of orbit. One of them, the Microgravity Science Glovebox (MSG), was developed by ESA within a barter agreement with NASA. The 'gloves' are the access points through which astronauts can manipulate experiments, see Fig. 1. The Glovebox provides the ability to perform a wide range of

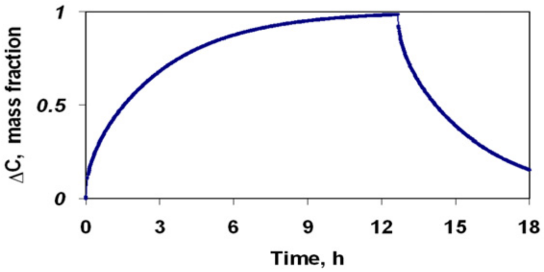


Fig. 3. Numerical simulations of typical IVIDIL experiment at the absence of vibrations. Components separation with time for liquid with negative Soret: 10% IPA–90% water.

experiments in the fields of material science, biotechnology, fluid science, combustion science and crystal growth research, in a fully controlled environment.

ESA's SODI multi-user facility (Selectable Optical Diagnostics Instrument) was initially developed for conducting three experiments: IVIDIL, DSC and Colloid. It was installed inside the MSG on the September 23, 2009. Hardware development was provided by Verhaert Space NV (Kruibeke, Belgium) and optical development was provided by Lambda-X (Nivelles, Belgium). Each experiment has its own dedicated cell arrays which are mounted into the SODI facility by the ISS crew. The experimental organization reminds Russian "matreshka", i.e. a set of facilities of decreasing sizes placed one inside the other: Glovebox → SODI → IVIDIL.

First in the sequence, the experiment IVIDIL started on the October 5, 2009 and total 55 experimental runs (41 original runs and 14 repetitions) were successfully completed by January 20, 2010. Each original run lasted 18 hours and all of them were controlled via telescience provided by the Spanish User Support Center (E-USOC, Madrid). For scientific examination of experiments 283 digital images were downloaded for each run. The major part of the images has recently returned on Earth on flash disks and will need extensive work during months. The results below are obtained on the basis of images which were downloaded via telemetry.

2.2. Experimental procedure and substances

In binary mixtures, one can distinguish positive Soret effect, when the lighter component is driven towards the higher temperature region (in accordance with gravity), and negative Soret effect, when the situation is opposite. Two mixtures of water and isopropanol (IPA) of different concentration are chosen as test fluids. First 26 runs were devoted to the mixture of 10% IPA and 90% water, which has negative Soret coefficient, $S_T < 0$. The following 29 runs used mixture of 50% IPA and 50% water which has positive Soret coefficient, $S_T > 0$. Both mixtures were degassed at MRC, ULB before the cells filling.

Each experimental run is performed in two steps. During the first step (duration of 12 hours) a concentration gradient is established by imposing a temperature gradient across the experimental cell to a uniform mixture. Due to the Soret effect, the concentration profile is slowly generated from an initially homogeneous binary mixture. After 12 hours the temperature gradient is removed and diffusion occurs during 6 hours. The vibrations of different amplitude and frequency are applied during these 18 hours.

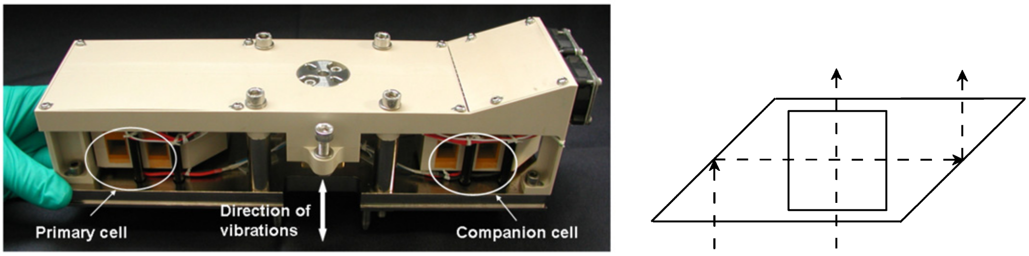
The separation of the components between the hot and cold walls, $\Delta C(t) = C_{\text{hot}}(t)–C_{\text{cold}}(t)$, during entire experimental run at the absence of vibration is shown in Fig. 3 for mixture with negative Soret. Fig. 3 shows numerical results where components separation $\Delta C(t)$ is normalized by its value at steady state in absence of mass fluxes, $\Delta C_{\text{st}} = -S_T C_0(1 - C_0)\Delta T$. Here C_0 is the initial concentration; ΔT is applied temperature difference between horizontal walls. For this calculations the values of Soret and diffusion coefficients were taken from literature [9,10].

The choice of experiment duration is a kind of compromise between relaxation time and available microgravity time. Diffusion relaxation time for the first liquid is $\tau_r = L^2/\pi^2 D = 3.25$ h and 12 h duration of non-isothermal step is sufficient to approach to steady state. Here L is the cell size in the direction of temperature gradient; D is the mass diffusion coefficient.

2.3. The IVIDIL instrument

All the current and future experiments conducted inside SODI facility are supposed to use available optical diagnostic. The IVIDIL experiment employs Optical Digital Interferometry and Particle Image Velocimetry. The IVIDIL instrument consists of three principal parts (see Fig. 2):

(1) Mach–Zehnder Interferometer in combination with equipment for digital recording the phase information;
(2) the diffusion cell;
(3) vibrational stimuli.



(a) (b)

Fig. 4. (a) Photo of core part of IVIDIL configuration; by courtesy of Verhaert Space. (b) Top view of each cell. The arrows show two optical paths.

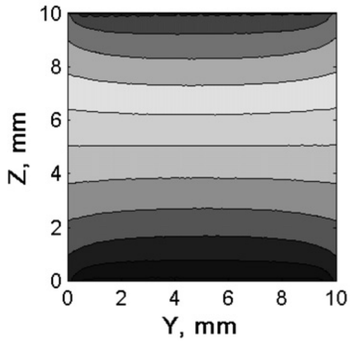


Fig. 5. (*Run 2*). Isolines of measured optically temperature field; applied $\Delta T = 5$ K, the distance between lines is 0.5 K.

The prototypes of all these parts were designed, developed and tested on the ground [11] or during parabolic flight experiments by MRC, ULB [12–14]. Hereafter we will shortly describe the cell array as it should be re-designed for any future experiment.

A dedicated cell array was designed and built for each IVIDIL mixture, see Fig. 4(a). The dimensions of the cell array are 8.5 cm (h) $\times$ 8 cm (w) $\times$ 30.5 cm (l). It consists of 2 identical optical cells filled with the same liquid. The primary cell contains only liquid while the companion cell in addition contains tracer particles for analysis of convective flows. Each cell has internal cubic shape of size $L = 0.01$ m. The external lateral walls shaped in the form of two transparent prisms allow scanning the front and side views, see the top view of the cell on the right side in Fig. 4(b). It enables anticipation of flow pattern which will be confirmed later by tracers and numerical modeling. The availability of two perpendicular views of the cell allows us to determine three-dimensional coordinates (positions) of the tracer particles. The tracers are hollow ceramic microspheres with radius 75 ± 20 μm which matched by density at mean temperature. Accordingly, two identical lasers and CCD cameras are used for the simultaneous cells monitoring as outlined in Fig. 2.

3. Results and discussion

If measurement methods are to be conceived, a proper understanding of the physics behind is needed. This will be the subject of this section. Hereafter we discuss results for Run 2: no vibrations, applied temperature difference $\Delta T = 5$ K, liquid with negative Soret effect: 10% IPA and 90% water. This run was repeated twice. First promising results below are obtained on the basis of images which were downloaded via telemetry in quasi real time during the experiment.

Comprehensive preparatory activity has been continued during a few years which resulted in a beneficial effect: all softwares were ready and minor problems with onboard experiment were identified and relevant solution found by the end of the first week. The level of onboard g-jitters was recorded by SAMS and decoded by science team.

3.1. Temperature and concentration fields

On the numerical side all runs were calculated and analyzed in physically realistic regimes. Time dependent 3D Navier–Stokes, heat and mass equations have been solved for each run prior to the experiment. In this analysis some idealizations are made compared to current measurements. One of them is the thermal boundary condition on vertical walls. The optical cells have very complex external shape, see Fig. 4(b). Using our previous experience [13] the *linear* temperature profile was imposed on lateral walls in computations. Processing of experimental images did not confirm this assumption. The temperature field in the experiments (Run 2, no vibration) shown in Fig. 5 displays that the temperature is linear at the central part with slowly increasing horizontal heat fluxes towards the cell corners.

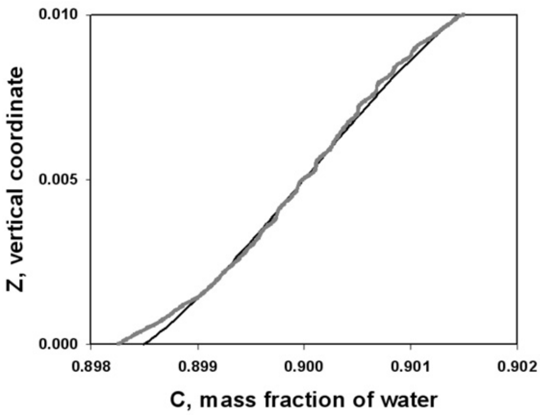


Fig. 6. (*Run 2*). Concentration profile across the cell; gray line shows experimental results from the ISS and black line corresponds to the numerical simulations.

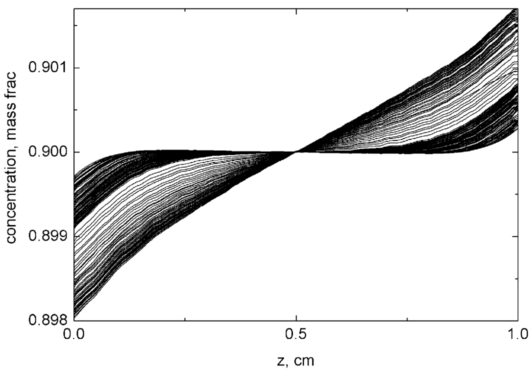


Fig. 7. (*Experimental results*) Concentration profiles in the direction of temperature gradient at different times. Non-uniform sampling rate is due to limited number of downloaded images.

Post-flight numerical re-simulations for Run 2 have been performed taking into account temperature profile on side walls from the experiment. The concentration profiles measured onboard by ODI technique and "post-flight" numerical one are shown in Fig. 6 at $t = 12$ h. An excellent agreement between computed results and experimental data demonstrates that the onboard experimental measurements and numerical code are capable to capture correctly the main characteristics of the considered phenomenon.

3.2. Mass transport coefficients

The mass transport coefficients cannot be measured directly. The experimental run may be conceptually split into three phases: (1) because liquid thermal conductivities are relatively large, a linear temperature profile is set up over a very short time interval; then (2) a transient separation of species profiles is followed by (3) a final steady state. The transient relaxation is theoretically tied to the mass diffusion coefficient, whereas the final steady state is tied to the thermal diffusion coefficient. However using ODI technique in IVIDIL experiment enables determination of Soret coefficient twice: in steady state and in transient regime using two-parameter fitting.

Each time a measurement is taken, a full concentration distribution over the thermodiffusion path is determined (similar to temperature field in Fig. 5). From this knowledge the concentration profiles across the cell are obtained at successive time moments, which are shown in Fig. 7 starting from early beginning and up to steady state; the single profile at $t = 12$ h was shown in Fig. 6. From the sequence of such concentration profiles the evolution of components separation with time $\Delta C(t)$ can be obtained between two arbitrary points in the direction of temperature gradient (z-direction). The experimentally obtained transient path between hot and cold walls $\Delta C(t)$ over 18 hours is presented in Fig. 8. Qualitatively this dependence is similar to the theoretical curve in Fig. 3 although coefficients of interest S_T and D are different.

The simplest procedure to find Soret and diffusion coefficients is to compare the concentration measured at point z_i at time t_j with its theoretical value using initial guess for S_T and D. The present technique gives a unique possibility of increasing measurement accuracy by providing information about concentration distribution along the whole thermodiffusion path. In fact, the method gives two-dimensional concentration field, although in the microgravity the distribution itself is almost one-dimensional due to the absence of convection. However non-linear temperature distribution (as shown in Fig. 5)

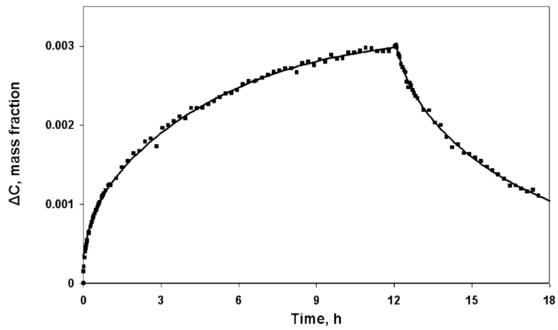


Fig. 8. (*Experimental results*) Component separation $\Delta C(t) = C_{\text{hot}} - C_{\text{cold}}$ with time over Soret (12 h) and diffusion (6 h) steps. Symbols indicate experimental points. The solid line is guide to the eye.

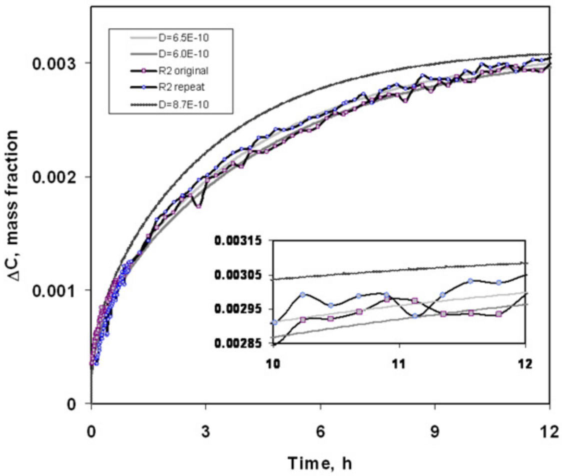


Fig. 9. Result of fitting. Curves with symbols correspond to the experimental results of two repetitions. Two gray curves without symbols show numerical results for currently measured diffusion coefficients D_1 and D_2 while black curve corresponds to $D_{\text{Ref. [12]}}$. Insertion shows magnified part at the 2 last hours.

Table 1
Measurements of Soret and diffusion coefficients onboard of the ISS.

	Transient, original run	Transient, repetition	Steady state original run	Steady state repetition	Mean value	Literature
S_T, 1/K	-6.95×10^{-3}	-7.02×10^{-3}	-6.44×10^{-3}	-6.66×10^{-3}	$(-6.77 \pm 0.11) \times 10^{-3}$	-7.08×10^{-3} Ref. [11]
D, m^2/s	6.0×10^{-10}	6.5×10^{-10}	6.425×10^{-10} (relaxation step)		$(6.31 \pm 0.127) \times 10^{-10}$	8.70×10^{-10} Ref. [12]

provokes additional disturbances and leads to increasing of error bar while using 1D analytical formula for fitting [7]. At present step 2D direct numerical simulations were used for two-parametric fitting procedure: S_T and D.

The results of fitting during Soret step are shown in Fig. 9, where the curves with symbols correspond to onboard experiment and its repetition during Soret step. Curves without symbols show numerical results for two slightly different coefficients of diffusion: $D_1 = 6.0 \times 10^{-10}$ m^2/s and $D_2 = 6.5 \times 10^{-10}$ m^2/s. One of the experiments fits better to diffusion coefficient D_1 while another to D_2. The third value of diffusion coefficient, $D_3 = 6.425 \times 10^{-10}$ m^2/s was obtained from diffusion step, i.e. during last 6 hours as shown in Fig. 8.

Four values were determined for Soret coefficient: two from transient regime and two from steady state. They are summarized in Table 1.

As follows from Table 1, the Soret coefficient measured on the ISS is relatively similar to the literature value and the difference is less than 5%. Note, that the authors of Ref. [9] mentioned a large error bar in their flow cell method.

However the mean value of diffusion coefficient $D_{\text{ISS}} = (6.31 \pm 0.127) \times 10^{-10}$ m^2/s differs by 38% from the previous value $D_{\text{Ref. [12]}} = 8.7 \times 10^{-10}$ m^2/s from Ref. [10]. We believe that our value is correct and we have several arguments for this.

First, introducing the diffusion coefficient into our simulations, results in a curve that lies far away from the experimental ones in Fig. 9 (upper black curve). Second, we may use the analogy between mixtures of water–IPA and water–ethanol.

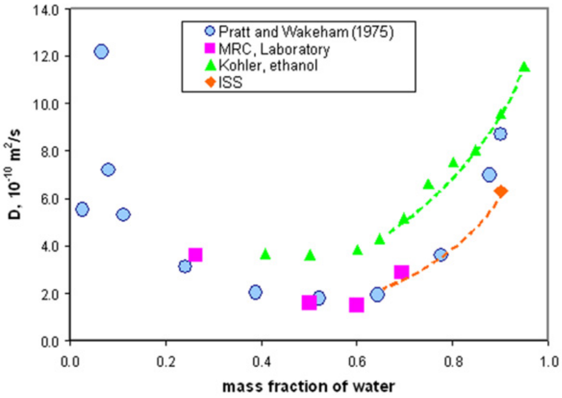


Fig. 10. Diffusion coefficient versus mass fraction of water for two aqueous solutions: water–IPA and water–ethanol (triangles).

Fig. 10 shows the diffusion coefficient versus mass fraction of water for two aqueous solutions: water–IPA and water–ethanol. Triangles correspond to the recent measurements in the water–ethanol mixture [15], while the other symbols correspond to Water–IPA data from different sources. The value measured onboard for $C = 0.9$ is shown by a rhomb, while circles represent values from [12].

Let us put dashed lines onto the plot as visual guides, for both aqueous mixtures and for water concentrations $0.7 < C < 0.9$. Only the newly measured value from the ISS provides a similar trend for both aqueous solutions. It gives confidence to our result.

The aim of any measurement is to estimate the “true” value of physical quantity. However, we never know the “true” value and there is always uncertainty associated with the measurement.

4. Conclusion

The main scope of this work is to present the IVIDIL experiment, which has successfully been completed on the ISS in January 2010. Live interferometric images were received during the experiment by telemetry and good quality experimental data was stored on flash disk and recently returned to Earth.

A general description of the ISS facility related to the experiment is shortly presented, as well as the description of the IVIDIL instrument and the successive steps of the experimental procedure. The first scientific results were obtained on the basis of images downloaded in real-time during the experiment via telemetry.

The results of experiments without vibrations (Run 2) for the mixture 10% IPA–90% water are discussed in depth. Using optical digital interferometry (ODI) on Earth for this liquid with a negative Soret effect would lead to instability. The onboard measurements have allowed determining the Soret coefficient in both transient and steady regimes. Averaging the measurements gives $S_T = -(6.77 \pm 0.11) \times 10^{-3}$, which is in good agreement with the literature value. On the other hand, the diffusion coefficient, $D = (6.31 \pm 0.127) \times 10^{-10}\ \text{m}^2/\text{s}$, differs from the previous measurements by 38%.

After comparing numerical and experimental results, as well as thoroughly analyzing the imperfectness of the measurements, we have drawn the conclusion that the ISS results are fully viable, and we are confident in these results. Guidelines have been drawn for justification of the results in favor of the Space experiment.

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