IVIDIL: on-board g-jitters and diffusion controlled phenomena

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Abstract. The experiment IVIDIL (Influence of Vibrations on Diffusion in Liquids) has been performed in 2009-2010 onboard the ISS, inside the SODI instrument mounted in the Glovebox at the ESA Columbus module. 55 experimental runs were carried out and each of them lasted 18 hours. The objectives of the experiment were multi-fold and here we report results for one of them. After each space experiment there is a discussion about the role of onboard g-jitters. The attention is focused on reproducibility of the results, their accuracy and comparison with numerical simulations conducted in exact geometry and using the physical properties of the system. We shortly report on the results of six experiments which were performed in natural environment of the ISS without forced vibrations. Thermodiffusion process in the cells filled with binary mixtures was monitored by means of optical digital interferometry. Perturbations of the diffusion control processes by on-board g-jitters is not observed in nominal regime of the ISS. Perturbations of thermodiffusion process were observed in non-nominal regime of the ISS, e.g. attitude control maneuvers.

1. Introduction

Molecular diffusion occurs when a concentration gradient exists in a mixture: there is a net mass flux that tends to decrease the magnitude of this concentration gradient. To analyze the effect of temperature gradients on separation of components in liquids the thermodiffusion process, also called Soret effect, is considered. This effect is usually slow but can be quite important in the analysis of the distributions of components in oil reservoirs. The Soret coefficient \( S_T = D_T/D \) measures the separation of the components of a mixture subjected to a temperature difference.

There is no universal technique that works for measuring the Soret coefficient of any binary mixture. Each technique has its own limitations. 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 even in the case of heating from above. 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 leads to unstable temperature (density) stratification.
The microgravity environment is a unique tool for studying the behaviour of liquids and measurements of transport coefficients. Note that the benefits of microgravity environment on space platforms such as International Space Station (ISS) could be altered by the residual acceleration and vibrations (g–jitter). It can result from aerodynamic drag, non-ideal free falling, trembling of space vehicle, onboard machinery, and crews activity. The presence of high-frequency oscillations in the spectrum of g-jitters could significantly affect diffusion experiments. Such oscillations generate time–averaged convective flows which may disturb purely diffusive heat and mass transfer [1]. There is a large body of theoretical studies on the influence of g-jitters on liquid behaviour and diffusion (see e.g. [2]-[6]) in microgravity and only very few experimental studies addressed this topic.

One of the first experiments studying the impact of residual accelerations onboard a spacecraft on convection in differentially heated cylindrical cavities was performed by Naumann [7] on STS–95 and independently by Russian researchers in DACON [8]. In these experiments, the temperature was monitored at several fixed points. The results did not provide clear evidence of time-averaged flows and related heat transfer caused by periodic high-frequency g-jitter.

Experimentally the existence of averaged flows in non-uniformly heated fluids under vibrations in microgravity environment has been qualitatively indicated in the experiments on MIR station[9] and has been qualitatively demonstrated in TEVICON parabolic flight experiments in the frame of IVIDIL preparation [10]-[11].

The MEPHISTO data from the USMP-3 Space flight mission (1996) presented the first quantitative data on g-jitter effects on a directional solidification experiment [12]. However it was concluded that there is a lack of well-documented experimental results that can be used for verification of numerical modelling to provide reliable predictions of g-jitter effects.

Dedicated experiments were carried out on-board the Mir station using the Canadian MIM facility [13]. Their primary analysis indicated that diffusion coefficients in dilute binary metallic alloys depend upon the residual accelerations and the quality of microgravity. Recent thorough reanalysis of these original data claimed that very limited numbers of data were considered for post-flight analysis and the results from the liquid metal diffusion experiments conducted on MIR do not support the conclusions drawn [14].

One of the objectives of joint Russian-German experiments on-board Foton M3 (2007) was aimed at studying the influence of g-jitter effect on solidification front. However the grown crystals of Ge and GeSi were locally detached from the wall and had a characteristic shape with a “neck” due to a gas volume, which appeared at melting a semiconductor ingot . Under these conditions Marangoni convection occurs in the melt.

The latter citations clearly indicate the lack of the experimental data quantifying on-board g-jitters effects and demonstrate timeliness and the importance of the IVIDIL space experiment.

2. Experiment procedure

IVIDIL experiment was placed inside ESA SODI multi-user facility (Selectable Optical Diagnostics Instrument) which, in turn, was installed inside the MSG on the 23rd of September 2009. SODI was developed as a multi purpose Facility for conducting initially three experiments: IVIDIL, COLLOID and DSC. Hardware development was provided by QinetiQ Space NV (Kruibeke, Belgium) and optical development was provided by Lambda-X (Nivelles, Belgium). The first in the sequence, the experiment IVIDIL (Influence of Vibration on Diffusion in Liquids) started on the 5th October 2009. In total 55 experimental runs (41 original runs and 14 re-runs) were successfully completed by January 20, 2010. Each original run lasted 18 hours and all of them were controlled via telesience provided by the Spanish User Support Center (E-USOC, Madrid). Each experimental run was 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 in the initially homogeneous binary mixture. After 12h the temperature gradient is removed and diffusion occurs during 6 hours. The vibrations of different amplitude and frequency were applied during these 18 hours if it was prescribed, for more details see [16]-[17]. The level of onboard g-jitters was recorded by SAMS and decoded by science team. Six hours of preheating time for thermostabilization of the optical system was required after switching off SODI for weekend or due to technical reasons.

The IVIDIL experiment included 2 cell arrays: one mixture with negative and another with positive Soret effect, water (90%-isopropanol (10%) and water (50%)-isopropanol (50%), respectively. The physical properties of liquids are given in Table 1. The cell arrays were exchanged on 2 December 2009. Each cell array included two cells: a primary and a companion. The only difference between them is the added tracer particles in the companion cell.

3. Experimental technique

The temperature and concentration fields were monitored by measuring the variation of refractive index inside the cell by optical digital interferometry. The setup is based on the concept of Mach–Zehnder interferometer. The prototype of flight model was designed and developed in the laboratory prior to the experiment as well as corresponding software [18]. It enabled processing the control images in real time and introducing small corrections in the experimental procedure. The detailed description of optical digital interferometry as well as results from ground prototype can be found in [19]–[20].

The important part of the experimental setup is the diffusion cell. The working liquid is placed in a cubic cell with transparent walls of internal size \( L = 10 \) mm, see Fig. 2a. The cell is made of quartz Suprasil. The top and bottom walls are kept at constant temperatures \( T_{\text{hot}} \) and \( T_{\text{cold}} \), respectively, by Peltier modules. In the experiments, the mean temperature \( (T_{\text{cold}}+T_{\text{hot}})/2 \) was fixed at 25°C, while the applied temperature difference \( \Delta T = T_{\text{hot}} - T_{\text{cold}} \) was 5, 10 K or 15 K. The experimental cell is attached to the linear motor, which performs translational harmonic
oscillations perpendicular to the temperature gradient. In the experiments, the frequency and amplitude were varied in the ranges 0.5–2.8 Hz and 10–61 mm, respectively. The maximum vibrational acceleration $A_\omega^2 = 0.998 \, g_0$ was achieved at $A = 61 \, \text{mm}$ and $f = 2 \, \text{Hz}$ ($\omega = 2\pi f$). The upper limit for frequency increases with decreasing the amplitude.

The external walls of the cell are shaped in the form of two prisms (Fig. 2b) to allow optical observation in two perpendicular directions[11]. An example of interference pattern in front view of the cell is shown in Fig. 3. Interferograms are reconstructed by performing 2D fast Fourier transform (FFT) of the fringe image, filtering a selected band of spectrum, performing the inverse 2D FFT of the filtered result and phase unwrapping[20]. The interferograms are the only source of the scientific information in the IVIDIL experiment along with the housekeeping data. For scientific examination of running experiments 283 digital images were downloaded for each run via telemetry. Totally 653 images per run have been recorded and they have returned on Earth on flash disks a few months later.

The knowledge of phase shift gives information about the gradient of refractive index. For a given wavelength, the variation of the refractive index is

$$\Delta n(x, z, t) = \left(\frac{\partial n}{\partial T}\right)_{T_0, C_0} \Delta T(t) + \left(\frac{\partial n}{\partial C}\right)_{T_0, C_0} \Delta C(t)$$

where $\Delta T(t)$ and $\Delta C(t)$ are temperature and concentration variations at point $(x, z)$. The characteristic thermal time, $\tau_{th} = L^2/\chi$, is about 500 times shorter than the diffusion time,

|                   | $\rho$ (kg/m$^3$) | $\beta_T$ ($10^{-4}$ K$^{-1}$) | $\beta_C$ | $\nu$ ($10^{-6}$ m$^2$/s) | $\chi$ ($10^{-7}$ m$^2$/s) | $D$ ($10^{-10}$ m$^2$/s) | $S_T$ ($10^{-3}$ 1/K) |
|-------------------|-------------------|-----------------------|----------|----------------------------|--------------------------|------------------------|---------------------|
| $H_2O$(90%-IPA(10%)) | 984               | 3.1                  | -0.14    | 1.41                       | 1.3                      | 7.4                    | -7.08               |
| $H_2O$(50%-IPA(50%)) | 905               | 7.7                  | -0.25    | 3.10                       | 0.85                     | 1.62                   | 5.45                |

Table 1. The physical properties of the mixtures at 25°C.
\[ \tau_D = \frac{L^2}{D}, \] here \( \chi \) is the thermal diffusivity and \( D \) is the diffusion coefficient. Thus, the contributions from temperature and concentration are separated in time. The typical example of the temperature field 10 min after imposing temperature gradient is shown in Fig. 4 (Run 33). Beneficial part of this technique is that the records are done over entire cross-section of the cell in two perpendicular directions during the whole diffusive process. It allows observing the evolution of the process with time and investigating convection when it exists, [18], [21].

In the absence of vibration an approximate analytical solution describing the process separation in the diffusion cell can be written as [18]

\[
\Delta C(t) = -S_T C_0 (1 - C_0) \Delta T \left[ 1 - \frac{8}{\pi^2} \sum_{n,odd} \frac{1}{n^2} \exp \left( -\frac{n^2 t}{\tau_r} \right) \right].
\] (2)

here \( C \) is the concentration of denser component, \( \Delta C(t) = C(L, t) - C(t) \) is the concentration difference between hot and cold sides of the cell, \( C_0 \) is the initial concentration of homogeneous mixture and \( \Delta T \) is the imposed temperature difference. In Eq.(2) there are two unknown parameters: the Soret coefficient \( S_T \) and the relaxation time \( \tau_r = \frac{L^2}{\pi^2 D} \). By fitting numerous experimental (Eq.1) and theoretical (Eq.2) points for \( \Delta C(t) \) from the beginning to several characteristic times the two unknown parameters \( S_T \) and \( \tau_r \) are determined. The value of Soret coefficient can be also obtained from the steady state, \( t \to \infty \)

\[
\Delta C = -S_T C_0 (1 - C_0) \Delta T.
\] (3)

In the case of the observation of the lighter component the sign will be positive.

4. Results and discussion

The primary goals of this manuscript is to clarify the role of onboard g-jitters. For this reason only runs without imposed vibrations are considered which are listed in Table 2 in chronological order. In the second column the Run identification is given according to "Daily Operations Report” during the experiment if someone in future would like to verify results as it was the case [13], [14]. Two experiments without vibrations were performed for the liquid with negative Soret effect, \( H_2O(90\%)\)-IPA(10\%), and four experiments for the liquid with positive Soret effect. In the case of experiment repetition (letter "R") the starting time allows to identify what is the time lag between the experiments.
Table 2. List of the experiments without imposed vibrations.

| Mixture               | Run | ΔT  | start (time,date) | initial condition | μg condition |
|-----------------------|-----|-----|-------------------|-------------------|--------------|
| H₂O(90%)-IPA(10%)     | 2   | 5   | 11:37, 07/10/09,  | after break       | nominal      |
| H₂O(90%)-IPA(10%)     | 2R  | 5   | 13:58, 11/11/09,  | after 15R         | nominal      |
| H₂O(50%)-IPA(50%)     | 3   | 15  | 18:25, 10/12/09,  | after run32       | nominal      |
| H₂O(50%)-IPA(50%)     | 1N  | 5   | 10:32, 12/01/10,  | after run36       | perturbed*   |
| H₂O(50%)-IPA(50%)     | 2N  | 10  | 05:04, 13/01/10,  | after run 1N      | nominal      |
| H₂O(50%)-IPA(50%)     | 33R | 15  | 17:20, 15/01/10,  | after run 3N      | nominal      |

*One of the experiments, Run1N, has been performed during ISS activities which may imply microgravity disturbances:
- ESP3 relocation between 14:25-15:55 GMT
- ISS attitude control maneuvers happened at 15:00 GMT (5 minutes duration)
- MT Translation moving the ESP3 platform between 17:35-19:35 GMT (thrusters were disabled during the activity).

4.1. First cell array, 90%H₂O – 10%IPA

Each time a measurement is taken, a full concentration distribution over the thermodiffusion path is determined (similar to temperature field in Fig.4). From this knowledge the concentration profiles across the cell are obtained at successive time moments; the single profile at t = 12h is shown in Fig.5 for denser component, i.e. water. The pink curve shows experimental dependence for Run2 while dark blue curve corresponds to numerical simulations performed for exact parameters of the system. From the sequence of such concentration profiles the evolution of components separation with time ΔC(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 ΔC(t) = C(L, t) − C(0, t) over 12 hours is presented in Fig.6 for original Run2 and its repetition one month later. The smooth behavior of curves and excellent reproducibility indicates that either onboard g-jitter is not important or absolutely identical during the month.

![Figure 5](image1.png) Concentration profiles over the height of the cell, ΔT = 5 K.

![Figure 6](image2.png) Separation of the components with time.

The IVIDIL results and numerical simulations.
In experiments without vibrations with the mixture displaying negative Soret effect the imposed temperature difference was $\Delta T = 5 K$ (Run2 and Run2R). As follows from Eq. 3 the small $\Delta T$ leads to the small component separation, i.e. weak signal. Indeed, while the initial concentration is $C_0 = 0.9 \,(90\% H_2O)$ the measured variation is only 0.003 what is about 0.3% from initial value. Keeping in mind good repeatability, it indicates on the high accuracy of measurements. Two solid curves in Fig.6 correspond to numerical simulations for slightly different diffusion coefficients, $D = 6.0 \cdot 10^{-10} m^2/s$ and $D = 6.5 \cdot 10^{-10} m^2/s$. This excellent agreement between experimental and numerical results performed without g-jitters shows that even for weak signals effect of g-jitter on diffusion controlled phenomenon is not visible.

4.2. Second cell array, 50\%$H_2O - 50\%IPA$

The behavior of the mixture in the second cell array is very different from the first one and it is not only due to the different Soret sign, $S_T > 0$. The Soret coefficient for the 2nd mixture is 1.3 times smaller but the diffusion coefficient is about 5 times smaller, see physical properties of the mixtures in Table 1.

The thermodiffusion process starts not only near the hot and cold walls but also near lateral walls because of an additional lateral temperature gradient (see Fig. 4) due to technical design of the cell, as a result of so called non-ideality of the experiment. In the second mixture ($H_2O(50\%)-IPA(50\%)$) diffusion process is too slow to eliminate these lateral concentration variations. The distribution of the concentration in the cell 10 min after imposing temperature difference is shown in Fig. 7. It is clearly seen that due to thermodiffusion (Soret effect) the concentration field changes near the lateral wall. On long time scale it will diffuse and concentration field at t=15h (Fig.8) will be similar to the temperature field (Fig. 4).

Duration of the thermodiffusion process in the IVIDIL (t=12h) is not sufficient to reach the state similar to that shown in Fig. 8 for numerical results. Thus concentration field observed in the 2nd cell of IVIDIL at t=12h still contains some variation at the central part near the lateral walls, see Fig.9. Two views show concentration fields in two perpendicular directions at the central part, not on the walls.

However the transient process of the thermodiffusion step is well reproducible and after 12h converges to the same final state shown in Fig.9. The transient behavior of run 33 and 33R

![Figure 7](image7.png) (Experimental results) Concentration fields 10 min after imposing $\Delta T = 15 K$, Run 33.

![Figure 8](image8.png) (Numerical results) Concentration fields 15h after imposing $\Delta T = 15 K$, Run 33.
Figure 9. (Experimental results) Concentration fields in two perpendicular directions at the central part of the cell at $t=12\text{h}$, $\Delta T = 15\, K$; Run33.

Figure 10. (Experimental results) Evolution of the component separation $\Delta C(t) = C(0, t) - C(L, t)$ with time when $\Delta T = 15\, K$; Run 33 and Run33R.

performed with time lag more than one month, including total stop of the SODI and Glovebox for three weeks of Christmas Holidays, displays good agreement between curves in Fig. 10. Note, that in this case dependence $\Delta C(t) = C(0, t) - C(L, t)$ is shown because of positive Soret sign. An excellent reproducibility enables confidence to the obtained results and does not display dependence of the diffusion process upon onboard g-jitters. The transport coefficients $S_T$, $D$ obtained by fitting the experimental curves in Fig.10 with the numerical solution Eq. (2) for the 2nd cell array are

$$S_T = 5.28 \times 10^{-3}\, 1/K, \quad D = 1.62 \times 10^{-10} m^2/s$$

The same coefficients should be recovered from all the experiment in the 2nd cell array, i.e. at

Figure 11. Evolution of the component separation $\Delta C(t) = C(0, t) - C(L, t)$ with time when $\Delta T = 5\, K$; Second cell array, Run 1N.
Looking at the perfectly reproducible results one may assume that the system under consideration is not sensitive to the microgravity perturbations. However it is not the case for strong microgravity disturbances caused by exceptional situations on the ISS. Run 1N has been performed during special activities on the ISS. Evolution of the component separation $\Delta C(t) = C(0, t) - C(L, t)$ with time for this experiment is shown in Fig. 11 where pink symbols correspond to the front view and blue symbols correspond to the side view. The continuous curve is the numerical solution with transport coefficients determined during the run without perturbations, i.e. by Eq. 4. Already at the first four hours experimental points display larger scattering than at nominal regime but they lie close to the numerical curve. It seems that preparatory activities by astronauts on the ISS started before the planned actions. As soon as system faced the microgravity perturbations the experimental points started to deviate from the theoretical curve and exhibit larger scattering. The strong peak perturbation at $\Delta t \approx 7h$ provides significant impact on thermodiffusion process and experimental points deviate stronger from the numerical curve.

During this run the SAMS instrument was attached to Glovebox and onboard accelerations (g-jitters) were recorded. The residual accelerations over the entire experiment in all three directions are shown in Fig. 12. The most distinctive peaks are correlated with perturbations of diffusion process. The detailed study of correspondence of the perturbations with the response of the diffusion cell is continued and will be published elsewhere.

5. Conclusions

Unprecedented experimental investigations onboard the ISS have been made to estimate the effect of g-jitters on diffusion controlled phenomena. The working liquids were binary mixtures of water and isopropanol of two different compositions. A temperature gradient was applied to the cells filled with initially homogeneous liquid. The component separation of the mixture caused by thermodiffusion has been thoroughly analyzed during 12 hours. The evolutions of the concentration field with time over the whole cross-section of the cell were monitored by means of

![Figure 12. Residual accelerations on the ISS recorded by SAMS during the IVIDIL experiment, Run1N.](image-url)
optical digital interferometry in two perpendicular directions. Alliance of digital interferometry and absence of convection allow to follow 3D time-dependent evolution of concentration and temperature fields.

Perturbations of the diffusion control processes by on-board g-jitter are not observed in nominal regime of the ISS. The experiments were repeated with large time lag and for different temperature gradients and they displayed an excellent reproducibility. For the runs without imposed vibrations the behavior of the experimental curves is in excellent agreement with numerical simulations when the ISS is operating in nominal regime.

Perturbations are visible in non-nominal regime of the ISS, e.g. orbit correction, docking, undocking, etc.

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