Human resources call - 2025

Project title : Non-isoviscous Turbulent Flows

Laboratories : IRPHÉ & IUSTI

Investigators : Gautier Verhille & Henri Lhuissier - PostDoc candidate: Julie Deleuze

IMI axis(es) : 4, 2

Disciplinary fields : Fluid Mechanics

Summary of the project:

This project tackles the challenging problem of the turbulent mixing of liquids with non-uniform viscosity. It will focus on the idealized case of the mixing of an initially spherical blob, which is more viscous than the surrounding fluid, in a uniform isotropic turbulent flow. The objective is to understand (1) the history of the blob deformation, (2) the mixing time, (3) the mechanisms and dependences of the process on the relevant parameters: viscosity ratio between the blob and the flow (ν/ν_0)*, Reynolds number of the flow* (Re_T)*, blob size relative to the flow (Kolmogorov) microscale* (d/ℓ_K)*, and relative mass diffusivity (inverse Schmidt number* D/ν_0*).*

The project launches a new collaboration between IRPHÉ (G. Verhille) and IUSTI (H. Lhuissier). It will leverage on the experimental facilities and expertise of IRPHÉ on turbulent flows, and on the model materials and expertise of IUSTI on laminar heterogeneous flows, to tackle an essentially unexplored field of research. The project will benefit from the experience and involvement of the high-level postdoc candidate, Julie Deleuze, on mixing in non-uniform high-Reynolds number flows.

This research is at the edge of mixing and aggregate fragmentation in turbulent flows, two hot topics in our communities. This project will allow IMI to be a leading actor in the field of mixing of non-uniform liquids.

1. Scientific project (2 pages max)

(Clarity of research objectives and hypotheses, scientific challenges, innovative character, originality and/or ambition, positioning in relation to the state of the art, potential economic, social or cultural impact, etc. . .)

1a. Context & General Question

Turbulent flows are efficient at dispersing and mixing substances (e.g., heat, nutrients, pollutants). While the underlying physics is understood for uniform fluid properties, much less is known when the substances to be mixed have a contrast in viscosity, although this problem is important for many geophysical and industrial contexts (e.g., mixing in planets core[1–3] or turbulent mixers[4,5], see figure 1*A*). In particular, it is not known: **How much does a non-uniform viscosity field change a turbulent flow? How is the viscosity field evolving through advection by the flow? How do viscosity contrasts affect the eventual mixing of the liquids?**

As pictured in figure 1*B*, the main difficulty lies in the coupling between the turbulent velocity field and the non-homogeneous viscosity field. Contrary to the mixing of a passive scalar, the flow dynamics depend on both the relaxation timescale of the viscous inclusions, especially when their viscosity is higher than the surrounding flow, and the timescale of turbulence. Moreover, contrary to immiscible fluids, which mechanical properties do not evolve with time, here subtle couplings can appear during the mixing, which changes viscosity, then the flow, then the mixing process.

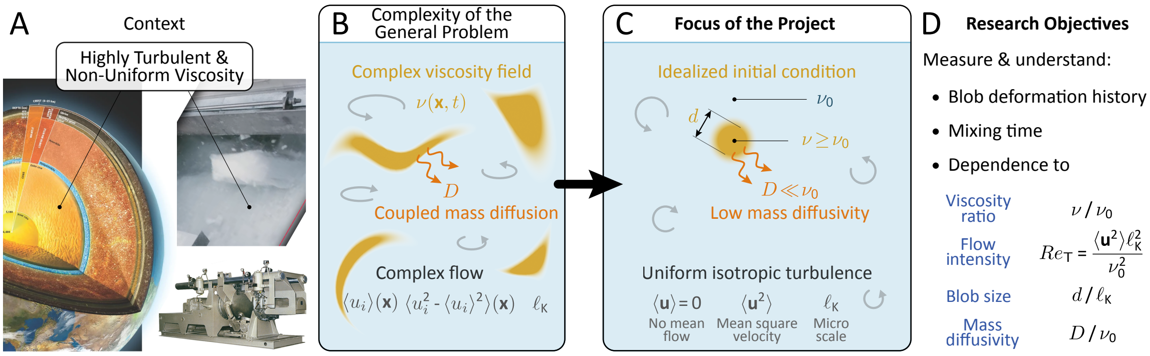

Fig. 1. Context, Focus & Objectives. (*A*) Turbulent flows of liquids with heterogeneous viscosity are found in planet cores, including the Earth outer core, and turbulent industrial mixers (adapted from [4–6]). (*B*) General complexity of the turbulent mixing of non-isoviscous liquids. (*C,D*) Strategy and research objectives of the project.

1b. Focus of the Project & Research Objectives

To achieve fundamental progresses on this vast problem, we choose to focus our project on an idealized configuration, which minimizes the number of parameters, while conserving most questions and couplings discussed above. We will consider the case (see figure 1*C*) of a more viscous and initially spherical blob, mixed in a uniform isotropic turbulent flow. This idealized configuration is amenable experimentally using IRPHÉ's turbulent facilities, IUSTI's materials and characterizations of viscous mixtures, and both labs visualization and imaging techniques (see §2). **The objectives are to measure and to model:**

1. **the deformation history of the blob**,
2. **the mixing time**,
3. **the mechanisms and dependences of the process on the four dimensionless parameters of the problem**: viscosity ratio between the blob and the flow (ν/ν_0), Reynolds number of the turbulent flow (Re_T), blob size relative to the flow (Kolmogorov) microscale (d/ℓ_K), and relative mass diffusivity (inverse Schmidt number D/ν_0).

1c. Novelty

A few studies have addressed non-isoviscous turbulent mixing, but they have focused on jet configurations[7–11], or used global characterization[12], without observing the flow, scales or mechanisms behind mixing. Much more literature has considered non-fully-miscible phases, documenting transports of rigid objects[13–16], or focusing on the deformations of conformable objects[17–19], drops[20,21] and bubbles[22–26]. However, because of elasticity or capillarity, these objects are not fluid and not unboundedly stretched by the flow, as a miscible liquid would be. To understand turbulent mixing of heterogeneous miscible liquids, it is then crucial to understand how such fluid, albeit non-isoviscous, objects are deformed by turbulence. **To date, no description of this deformation exists in literature. There is also no prediction for the mixing time, or the scales at which mixing occurs**.

1d. Challenges

These questions raise many challenges. The first one is the vastness and complexity of the general problem of non-isoviscous turbulent flows. It is partly addressed by focusing the study on the idealized case of an initially localized heterogeneity in viscosity in a uniform isotropic turbulent flow (see §1b). To model this phenomenon a statistical approach is required due to the inherent stochasticity of turbulence. Hence, a large number of challenging experiments is required to converge the statistics of the non-trivial coupling between the blob stretching and the alignement with the local straining rate. Moreover, as turbulence is a multi-scale forcing, the ratio of the blob size to the intrinsic turbulent flow scale (d/ℓ_K) has to be varied. Additionally, for high viscosity contrasts ($\nu/\nu_0 \gg 1$), we anticipate that the overall blob deformation is slow, compared with the shortest turbulent flow timescale $\sim \ell_K^2/\nu_0 \sim 1\,\mathrm{ms}$. This means it will be challenging to resolve both fast flow scales and the global deformation of the blob they achieve by slow cumulative effects. Last, the (Batchelor) scale at which mixing by molecular diffusion eventually proceeds is expected to be small ($\sim 1\,\mu\mathrm{m}$), which renders direct resolution in such a fast and rapidly varying 3D flow difficult.

1e. Feasibility

These challenges can be overcome. The key practical elements are in place (see §2b). Experimental techniques and the necessary theoretical elements are available to the consortium (see §2a). Finally, preliminary experiments we could conduct (see figure 2) have confirmed the strong signature of the viscosity contrast (ν/ν_0) on the dynamics and effective mixing time of the blob, which confirms that important experimental and phenomenological modeling will be obtained.

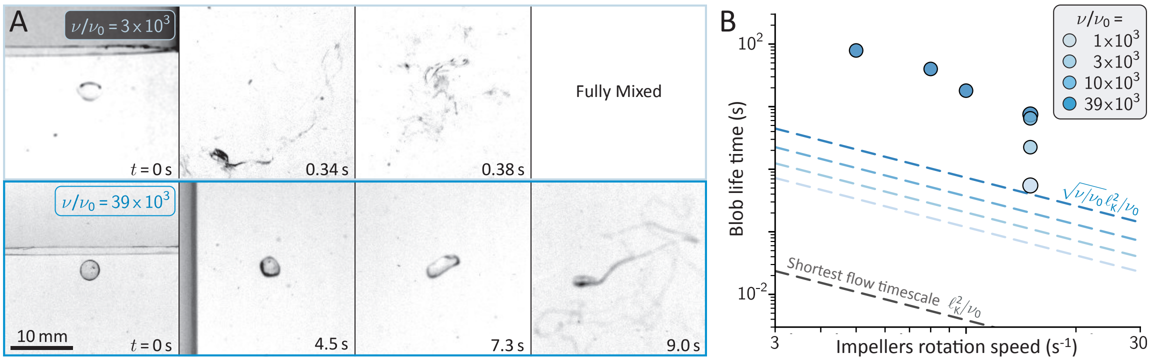

Fig. 2. Preliminary experiment. A. Two highly viscous blobs ($\nu = 3$ and $39\,\mathrm{Pa\,s}$) in a turbulent water flow ($\nu_0 = 1\,\mathrm{mPa\,s}$). **The stretching and mixing times of both blobs (~ 1 - $10\,\mathrm{s}$) are orders of magnitude longer than the flow micro-timescale $\ell_K^2/\nu_0 \sim 1\,\mathrm{ms}$.** The impellers rotation speed is $15\,\mathrm{s}^{-1}$, the Taylor scale Reynolds number is $Re_T \approx 470$, the (Kolmogorov) microscale is $\ell_K \approx 30\,\mu\mathrm{m}$, the blob size is $d \approx 3\,\mathrm{mm}$. **B.** Rough estimate of the blob mixing time for different viscosity contrast (ν/ν_0) and turbulence intensity ($\propto$ rotation speed^3).

2. Funding added-value

(Complementarity of skills & methods, multi-disciplinarity, risk-taking in the research project, pooling of equipment...)

2a. Complementarity of skills & methods

This project is collaborative and builds on the complementary of skills and methods brought by the 3 protagonists: **IRPHÉ** (G. Verhille), **IUSTI** (H. Lhuissier) and the **PostDoc** candidate (J. Deleuze).
Gautier Verhille has developed a strong experimental and theoretical expertise on turbulent flows, in particular, on the deformation[27] and fragmentation[28] of conformable objects (such as flexible fibers and discs[18]) by these flows. He has developed methods and algorithms to track and model deformation and fragmentation events in 3D, which will be used for the project (see §2b).
Henri Lhuissier brings his experimental and theoretical expertise on deformation statistics and mixing in low-Reynolds chaotic flows[29–31] and, in particular, model experimental systems and modeling methods which have permitted to understand mixing of viscous heterogeneities in chaotic flows[32,33] (see figure 3).
Julie Deleuze brings her experience, as well as experimental and theoretical skills on heterogeneous flow preparation, high-Reynolds flow imaging (PIV, PTV), and mixing characterization (PLIF, Schlieren technics)[34–37]. **Since Julie Deleuze's profile and skills perfectly match this project, and in response to her high motivation, we have hired her for 3 months** (on a terminating credit line) **to avoid she applied to another position, and to give her a chance to apply to the present IMI call and start handling the intense experimental campaign needed for this research**.

2b. Pooling of equipment

The project is made possible by the following pooling of material, equipments and methods.
IRPHÉ provides the turbulent flow platform (see figure 3), with calibrations and flow visualization techniques. It also provides fast-imaging material and reconstruction methods to track in-situ 3D deformation of objects and compile converged statistics. Moreover, IRPHÉ recently acquired Shake The Box (LaVision), a cutting edge Particle Tracking Velocimetry algorithm, which will be used to measure the flow around the blob.

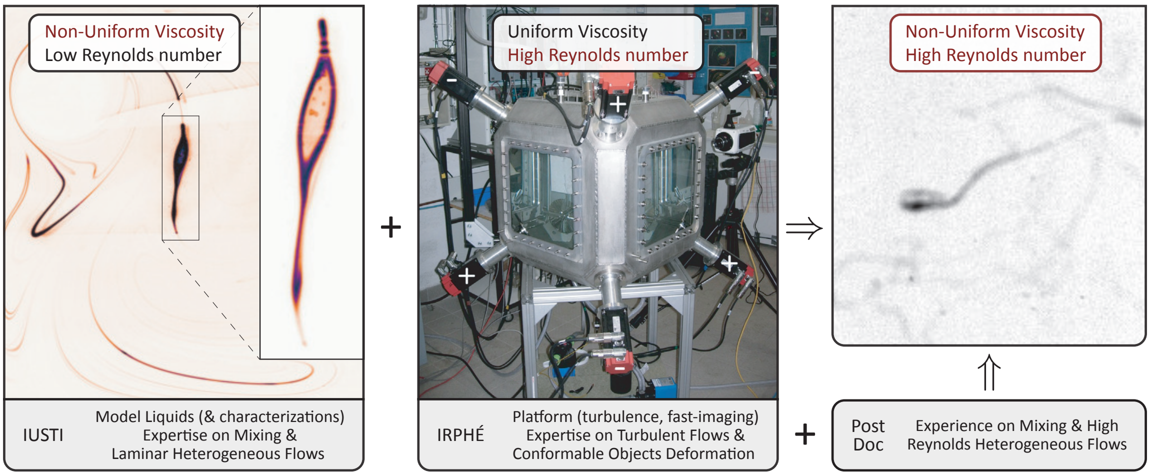

Fig. 3. Complementarity of skills & methods. (*Left*) Material & expertise brought by IUSTI from previous studies on the mixing of a viscous heterogeneity in a *non-inertial* chaotic flow $(\nu/\nu_0 \gg 1,\ Re \ll 1)$[32,33]. (*Middle*) Experimental platform & expertise brought by IRPHÉ: The Cube 'washing-machine' facility achieves close to isotropic turbulent flows with high Reynolds numbers (Re_T up to 650[38]). (*Right*) Together with the PostDoc candidate experience on heterogeneous high-Reynolds number flows, they will allow the consortium to efficiently tackle turbulent flows with non-uniform viscosity.

IUSTI provides model, water-miscible, Newtonian liquids of tunable viscosities ν with characterizations (viscosity, density and density-matching parameters, refractive index), including characterization of the mass diffusivity D[33]. IUSTI also provides the experimental techniques (calefacted freezing on liquid nitrogen bath + melting) used to create initially spherical blobs, as well as chemically synthesized dyed polymer, which will permit verifying in situ the polymer concentration (viscosity) across the blob.

This pooling leads to the following implementation. Experiments will be conducted using IRPHÉ's *Cube* facility: a 60 cm cube filled with water, with rotating impellers at each vertex. The impellers rotation generates a close to homogeneous and isotropic turbulent flow with high Reynolds number (Re_T up to 650) in a central core of $\approx 10\times10\times10\,\mathrm{cm}^3$. A chimney will be added to inject a blob of a Newtonian mixture of water and Ucon oil (a water miscible polymer) with a diameter $d \sim 1\,\mathrm{mm}$, directly into the flow core. The blob deformation and flow around it will be tracked with high-speed cameras (5 available), by seeding water with tracer particles. Images will be processed using in-house 3D reconstruction algorithms and the Shake The Box PTV algorithm.

Understanding the mixing process requires to vary systematically the viscosity ratio (ν/ν_0), the blob relative size (d/ℓ_K), and the relative mass diffusivity (D/ν_0). ν/ν_0 will be varied by changing the Ucon oil concentration in the blob. d/ℓ_K will be varied by changing both the blob size d and the flow microscale ℓ_K, through the impellers rotation speed. In the latter case, the flow Reynolds number will also vary. However, as the blob size lies in the inertial range of turbulence, this variation is not expected to change the mixing mechanisms. Finally, while keeping D/ν_0 small, we will vary the mass diffusivity D (using e.g. glycerol), to validate its influence on the mixing time.

2c. Risk-taking in the research project

The project takes the risk of addressing the complex and essentially unexplored field of high-Reynolds mixing of non-isoviscous liquids. This risk comes with the challenges listed in §1d: (i) general complexity and vastness of the problem, (ii) turbulence stochasticity and complex 3D coupling, (iii) broad range of time scales, (iv) broad range of length scales. To mitigate the risk and overcome the challenges we will use the following strategy.

(i) We focus the study to our relevant model configuration, which restricts the phase space to four dimensionless numbers (one of which, D/ν_0, is very small) we can control independently in experiments. If this phase space reveals to be too vast, we can further focus on the most interesting limit of large viscosity contrasts ($\nu/\nu_0 \gg 1$).

(ii) Our experimental protocols and imaging/analyses techniques are adapted to repeated experiments to obtain converged statistics. IRPHÉ's previous studies[18,27,28,39] have already overcome this difficulty. Also preliminary experiments suggest orders of magnitude influence of the viscosity contrast (ν/ν_0, see figure 2,*right*), which will facilitate interpretation and modeling.

(iii) The preliminary experiments show that, for the highest viscosity ratio ($\nu/\nu_0 \sim 4\times10^4$), mixing takes up to 10^4 flow timescales. In this case, tracking the flow with high-speed cameras is not the most relevant strategy. We will rather restrict simultaneous measurements of the flow and the blob deformation to experiments with a moderately long mixing time (high flow intensity and moderate viscosity ratio). Relevance for slower mixing (low flow intensity and large ratio) will be tested by comparing experimental mixing times with our predictions.

(iv) The mixing (Batchelor) scale ($\ell_B \sim \sqrt{D/\nu_0}\,\ell_K \sim 1\,\mu\mathrm{m}$) is too small and too separated from the blob scale ($d \sim 1\,\mathrm{mm}$) to be fully resolved by our imaging system. However, the investigation of a similar problem in a chaotic flow at IUSTI has showed that the mixing time does not depend, in practice, on the scale ℓ_B at which diffusive mixing eventually occurs, because the mixing time is dominated by the slow initial deformation, when the blob is close to spherical. In turbulence, this initial deformation regime is expected to be controlled by eddies with a size close to the blob size, and a coarse grained approach will be adopted.

3. Impact and spin-offs

(Scientific impact and potential economic, social or cultural impact, strategy for disseminating and exploiting results, including promotion of scientific, technical and industrial culture)

3a. Scientific impact

This project is mainly fundamental, therefore, the main expected results are the improvement of our understanding of transport and mixing in non-uniform turbulent flows and the development of a large data base compiling our results. From a Lagrangian turbulence perspective, this project is at the edge between several fields of research: transfers in loaded turbulent flows, the transport of elastic object for which stretching is generally negligible, the fragmentation of brittle objects like aggregates and the deformation of material line for which there is no resistance to stretching. This four fields of research are currently very active. We expect that our project will build bridges between these different topics and hence have an important impact in the community.

The large data base we will create will be shared with the community to foster collaborations, especially with theoreticians aiming to improve our modeling and with numericists aiming to benchmark their code and/or run complementary simulations to improve our understanding of the phenomenon. Note that, using direct numerical simulations to tackle this complex problem is currently a challenge due to the multi-scale aspect of the problem in both time and space and also due to the feedback of the mixing viscosity field on the flow, which prevents decoupling the flow problem from the mixing problem. For the time being, experimental evidences, measurements and simplified theory represent a necessary path.

3b. Potential economic, social or cultural impact

As mentionned earlier, this project is mainly fundamental and, currently, no contact with industrial partners, which might be interesting in optimizing their mixing progress has been established.

3c. Strategy for disseminating and exploiting results, including promotion of scientific, technical and industrial culture

The results will be disseminated through publications in fluid mechanics and soft matter journals. We also anticipate that the results could have the potential to be published in physics and more generalist journals, which would permit to access a broader audience. Results will also be presented by all three protagonists in national and international conferences and seminars. In particular, dissemination to diverse research communities in mechanics will be achieved by participating to the following GdRs: GdR Navier-Stokes 2.00 (Fluid Dynamics & Turbulence, to be renewed), GdR SLaMM (Complex Fluids & Soft Matter), GdR TransInter (Material Transfers & Phase Changes) and GdR MFGA (Geophysics & Astrophysics Fluid Mechanics).

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