NUMERICAL SIMULATIONS AND QUASI-NORMAL CLOSURE OF STRONGLY VARIABLE-VISCOSITY TURBULENT FLUID MIXTURES

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Abstract A remarkable property of turbulence is its ability to enhance the mixing of scalar contaminants, either passive or active. Consequently, the accurate prediction and/or control of these phenomena requires a thorough understanding of scalar mixing in turbulent flows and its dependence on (or, interconnection with) the dynamic field which transports it. A single, homogeneous fluid turbulence (CVF, Constant Viscosity Flow) has received much more attention. One of the important questions concern the validity of the Taylor's postulate, which predicates the independence of the mean energy dissipation rate of the viscosity, at sufficiently high Reynolds numbers.

However, heterogeneous mixing of fluids with variable viscosity (hereafter VVF, Variable Viscosity Flow) is widely present in real flows, either nonreactive or reactive. This contribution is dedicated to push forth our understanding of the turbulent mixing phenomenology, in a homogeneous isotropic turbulence (HIT) in which the initial condition is a complete segregation of the two fluids, which are allowed to mix together as time keeps increasing. The ratio of the viscosities is of $R_v \geq 10$, whereas their densities are very nearly equal. Therefore, the main physical property which differentiates the two fluids is their viscosity. The focus of this paper is on the role played by the viscosity variations on the small-scale statistics, over the first several integral times. The main question concerns the validity of the Taylor postulate in VVF.

For doing this, the numerical experiments for heterogeneous fluid mixtures proposed in [2] are revisited with an increased ratio of viscosity. In addition, a quasi normal closure is presented allowing to extend further the investigation of strongly variable-viscosity fluid mixtures. The impact of this effect on turbulence is discussed, and particular emphasis is given to the balance between different terms in the transport equation for the kinetic energy dissipation rate.

CONTEXT AND PROBLEM FORMULATION

Context. VVF flows are accompanied by a set of peculiarities, as it was emphasized for instance in [4], [3]. A turbulent propane jet discharging into an air-neon co-flow, for which the viscosity ratios was 5.5, was compared with a turbulent air jet discharging into still air. Both flows have the same initial jet momentum. As mixing with the viscous co-flow is enhanced with increasing downstream position, the viscosity of the fluid increases rapidly for the case of the propane jet. In comparison with the air jet, the propane jet exhibits: (1) a lower local Reynolds number based on the Taylor microscale (by a factor of four); (2) a reduced range of scales present in the flow; (3) the isotropic form of the mean energy dissipation rate is first more enhanced and then drastically diminishes and (4) a progressively increasing local Schmidt number (from 1.36 to 7.5) for increasing downstream positions. Therefore, the scalar spectra exhibit an increasingly prominent Batchelor regime with a '-1' scaling law.

All these observations led to the conclusion that viscosity variations may be important and act over the velocity field, even at the zero-order level. A clear definition of the Reynolds number, basically understood as the ratio between the inertial and the dissipative terms, is not available in VVF flows. The proposal of [3], albeit developed for jet flows, is intuitively extensible to other flows.

Recently, an important question has been addressed in [2] and concerns the validity of Taylor's hypothesis in VVF. This question encompasses two faces. First, it is the time evolution of the mean energy dissipation rate, $\varepsilon = \langle \mu \partial_j u_i \partial_j u_i \rangle$, [2], [3]. Second, is the transport equation of ε, in which supplementary terms are present, due to variable viscosity effects. Potentially, they can modify the classical balance between the dissipation production due to vortex stretching and the destruction term. However, in [2] no major effects due to variable viscosity have been detected, leading to the conclusion that Taylor's hypothesis is perfectly valid for such mixture flows. Although the ratio between the maximum and minimum of viscosity in this study was not negligible $R_v = \frac{\mu_{high}}{\mu_{low}} = 5$, it may not be sufficient to draw definitive statements.

In addition, more important ratio can be found for instance in practical applications such as propane/air ($R_v = 5$). Also even greater values like $R_v \geq 100 - 1000$ are observed in magmatic chambers [1] or in a mixture of high temperature plasmas during the implosion of a capsule used for ignition confinement fusion (ICF). The main objective of this work is therefore to verify the validity of Taylor's hypothesis to those more extreme configurations.

Our approach. We consider the incompressible Navier-Stokes equations under Boussinesq approximation for a velocity field u_i and a concentration scalar c, viz.

$$\partial_t u_i + u_j \partial_j u_i = -\partial_i p + \partial_j \left(\mu(c) \partial_j u_i \right), \tag{1}$$

$$\partial_i u_i = 0, \tag{2}$$

$$\partial_t c + u_j \partial_j c = \partial_j \left(D \partial_j c \right), \tag{3}$$

where μ is a variable viscosity which depends linearly on the concentration as follows

$$\mu(c) = \mu_{high} + c\,(\mu_{low} - \mu_{high})\,, \tag{4}$$

and D is a constant molecular diffusion coefficient, considered as being equal to the highest viscosity value, $D = \mu_{high}$. These equations are different from the classical Boussinesq turbulence. Here, the mixture fraction c is an active parameter in the momentum transport equation (1), via the variable viscosity coefficient. Therefore, the scalar c represents an active scalar and the two transport equations are coupled. Numerical simulations of VVF are not trivial because the resolution has to be adjusted on the lowest value of viscosity. Therefore, investigating relatively large Reynolds numbers of VVF with numerical simulations naturally leads to using models, applicable directly to statistics (e.g., spectra). The linear law of viscosity chosen (4) has the advantage of generating quadratic terms in the momentum equations (1). Transport equations for different statistics may be closed using a quasi-normal approximation. Using this procedure a full EDQNM model can be written for the problem allowing to study very large viscosity ratios.

FIRST NUMERICAL RESULTS

We solve (1-3) using a spectral code for the first test case proposed in [2] with $R_v = 10$ and a resolution of 1024^3. The initial condition is HIT. The two halves of the box are initially characterised by different viscosities, and mixing occurs as time evolves. Figure 1 (left) illustrates an instantaneous image of velocity and scalar fields at $\tau \approx 0.1$ integral time scales.

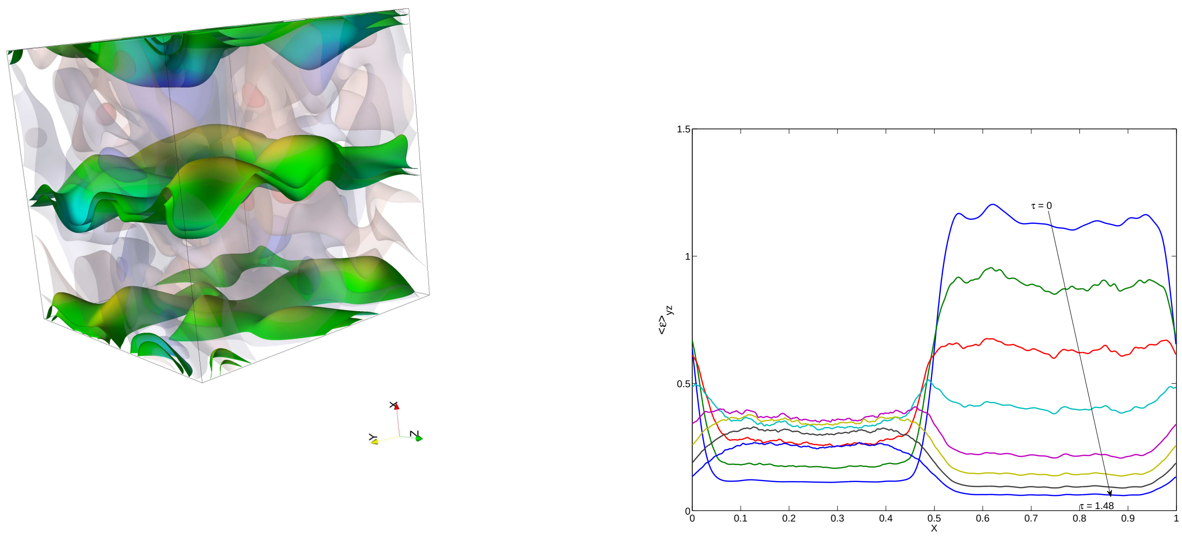

Figure 1. Left. Instantaneous visualization of the flow. Green: iso-surface of viscosity. Pink: iso-surface of velocity. Right. Variation of the dissipation rate averaged along the xy-plane and evolving with time $\tau = t\langle \frac{\varepsilon}{k} \rangle_{t=0}$.

The top half of the box bears the higher viscosity, whereas the lower part of the box is 10 times less viscous.
Whereas at the initial time, the mean energy dissipation rate (Fig. 1, right) is much more important in the viscous half of the box, it undergoes an uniformisation as time keeps increasing. Further investigations are being performed in order to conclude on the pertinence of Taylor's postulate and to provide a clearer landscape of VVF.

References

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