VARIABLE-VISCOSITY MIXING IN THE VERY NEAR FIELD OF A ROUND JET

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Abstract We carry out a comparison between Constant Viscosity Flows (CVF) and Variable Viscosity Flows (VVF), in a round jet, on the basis of the same initial jet momentum. It is found that viscosity variations have a non-negligible impact on mixing. VVF exhibit an acceleration of the trend towards isotropy and self-similarity. Some fundamental turbulence parameters, such as the true Reynolds number (Re), as well as the mean dissipation rate ($\bar{\epsilon}$) are expressed and discussed in the context of VVF.

MEAN VELOCITY PROFILES AND REYNOLDS NUMBER

The flow facility is a $5mm$ diameter (D) jet injected in a slight coflow. The two situations we consider here fundamentally differ in virtue of the viscosity ratio $R_v = \frac{\nu_h}{\nu_l}$, where ν_h and ν_l are respectively the higher and lower kinematic viscosities. In this study, the rapid/jet fluid is less viscous, whereas the slow/coflow fluid is more viscous by a factor of R_v. The experimental conditions are provided in Table 1. More specifically, the considered cases are the following:
-CVF. An air jet issues in a coflow of air. The viscosity ratio $R_v = 1$.
-VVF. A propane jet issues in a coflow of oxidizer (30% air and 70% neon). The latter is 5.5 times more viscous than the propane, so that $R_v = 5.5$. The density ratio is very almost equal to 1.
The comparison between CVF and VVF is based on the *same initial condition*, i.e. the same initial jet momentum, therefore almost the same injection velocity U_0. *At issue are the fundamental differences in the behaviour of VVF versus CVF, for the same initial conditions*. We further our understanding of this subject, by using both analytical and experimental tools. Two components of the velocity field have been measured using LDV (Laser Doppler Velocimetry), whereas the concentration field was quantified via Rayleigh scattering. The reader is referred to [3] for more details on the experimental set-up and measurement techniques.

Case	Injected Fluid	Coflowing Fluid	U_0 (m/s)	U_{coflow} (m/s)	Re_D	M_0 $(kg \cdot m^{-1} \cdot s^{-2})$	$R_v = \frac{\nu_h}{\nu_l}$ h=higher, l=lower
CVF	Air	Air	10.5	0.15	3300	130	1
VVF	C_3H_8	Oxidizer	8.5	0.15	9200	130	5.5

Table 1. Experimental flow conditions.

The analysis of the radial profiles of longitudinal mean velocity $\overline{U}(r)$ provides a quantitative way to compare CVF and VVF (Fig.1). A stronger decrease of $\overline{U}$ in VVF than in CVF is noticeable, indicating an increased entrainment of the ambient fluid into the jet fluid and an accelerated trend towards self similarity. These observations are confirmed by the $\overline{V}(r)$ values (not shown here), which are larger in VVF than in CVF.

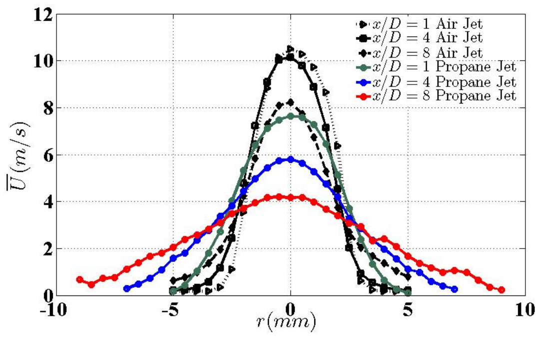

Figure 1. Radial mean velocity profiles $\overline{U}(r)$ for air (left) and propane (right) jets at M_0=130 $kg/m/s^2$, as a function of the radial position r normalised with respect to the jet half-width $y_{1/2}$, at three downstream positions $x/D = 1, 4$ and 8.

These experimental observations are corroborated with an analytical investigation of the mean momentum equations in VVF. Viscosity variations lead to supplementary terms (with respect to the classical CVF) [2]. These terms reflect correlations between viscosity gradients and fluctuating velocity. An increase of the viscous contribution results in a continuously decreasing ratio between the inertial and viscous effects. The consequences are twofold. First, the mean longitudinal velocity decreases faster in VVF than in CVF (for the same initial velocity). Second, the local Reynolds number varies in VVF. However, a local 'true' Reynolds number may be defined in VVF, Re_t. In the near field of the jet, Re_t involves a combination of ν_l, ν_h, $\overline{\nu}$, U_0 and D, viz.

$$Re_t = \frac{1}{\frac{\overline{\nu}}{U_0 \cdot D} + Re_D^{1/2} \cdot \frac{R_v - 1}{R_v^{3/2}}}, \tag{1}$$

In the immediate vicinity of the injection, this reduces to (also in agreement with the predictions of [1])

$$Re_t^0 = \frac{U_0 \cdot D}{\nu_h}. \tag{2}$$

As a result, an adequate comparison between VVF and CVF is to be done on the basis of the true Reynolds number at the origin, Re_t^0. More precisely, given a VVF for which the two fluids are known, the most adequate CVF flow with which the comparison is to be done is that involving the more viscous fluid (here, the air), and the same product $U_0 \times D_0$. Here, D_0 is the same, hence U_0 is (almost) the same.

FLUCTUATING FIELD AND ONE-POINT ENERGY BUDGET

The next step is to compare the RMS (root-mean-squared) of u and v (Fig. 2) in CVF and VVF with the same initial conditions and the same geometry. We observe more intense values of $RMS(v)$ as well as a faster tendency towards isotropy

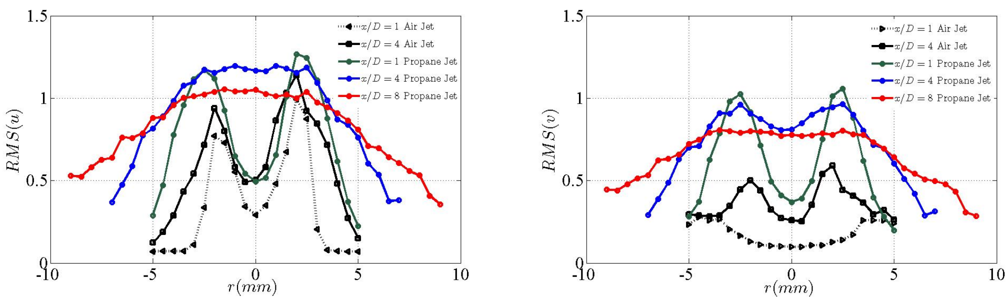

Figure 2. Standard deviation of fluctuating velocity profiles $\overline{u'^2}^{1/2}$ (left) and $\overline{v'^2}^{1/2}$ (right) for propane (VVF) and air (CVF) jets. M_0=130 $kg/m/s^2$, for x/D=1, 4 and 8.

in VVF than in CVF. The birth of these turbulent fluctuations most likely results from a combination of three factors: i)Kelvin Helmoltz instabilities; ii)wake instabilities behind the injector lip; or iii) interfacial instabilities due to viscosity jumps. i) and ii) are the same for both jets so they are not responsible for the differences between CVF/VVF. Viscosity variations lead to interface instabilities whose growth rate is maximum for the dynamical viscosities ratio $\mu_1/\mu_2 > 2.5$ [4] (here, $\mu_{oxidizer}/\mu_{propane} \sim 3.5$). Therefore, we conclude that interface instabilities associated with viscosity gradients are important and contribute to the enhancement of mixing.

We propose the following phenomenological scenario to explain the mixing enhancement. Viscous host fluid blobs are brought (via the three types of instabilities) into the jet fluid. These viscous blobs represent obstacles which slow down the initial jet velocity and lead to the production of radial velocity fluctuations behind these obstacles (wake instabilities). The rapid birth of radial velocity fluctuations accelerate the trend towards isotropy and self-similarity. Further analytical, experimental and numerical investigations are necessary to refine this scenario.

A deeper insight into the birth, increase and dissipation of turbulent fluctuations is provided by the one-point kinetic energy budget in VVF, which will be presented in the full paper. New terms, due to viscosity gradients, lead to an enhancement of the dissipation rate with respect to CVF. Obviously, many questions remain open, such as the value of $\overline{\epsilon}$ in different laboratory flows, or the normalised value of the energy dissipation rate.

References

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