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Enhanced liquid–gas mixing due to pulsating injection

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ABSTRACT

This paper considers the effects of intermittent injection of a liquid jet or spray on the initial break-up and mixing of one fluid with the surrounding ambient fluid. The aim of the analysis is to describe the physical process and indicate the mechanisms that control the mixing under different flow conditions (time-dependent injection and its frequency relative to the time scales of the flow) and fluid properties (density ratio), Schmidt number for a single phase case which is studied for comparison, or the Weber number for the two-phase cases. The computations use Large Eddy Simulation (LES) to account for turbulence, and either Volume Of Fluid (VOF) for the initial break-up or Lagrangian Particle Tracking (LPT) with droplet break-up model in the case of liquid droplets injected into the ambient gas. The results show that, depending on the physical properties of the liquid and ambient gas, the initial break-up and turbulent mixing can be enhanced substantially with intermittent injection. The numerical modeling is validated by recovering key results of experimental and analytical works. It can be observed that a main effect during the mixing is the suction of ambient fluid at the tail of the injected liquid, which depends on the fluid properties. Increased injection frequency shows to increase the mixing significantly during the initial transient phase.

1. Introduction

Turbulence is a well-known mechanism to enhance mixing. Steady, i.e. continuously injected, turbulent jets generate large scale vortices which enhance the large scale mixing and the entrainment of ambient fluid into the jet. The shear-layer of the jet produces also small scale turbulent eddies that are responsible for the local mixing. For many applications, such as a fuel jet injected into a combustion chamber, the time and space that is allowed for mixing is limited. The mixing time of a species by molecular diffusivity is proportional to l^2/D_m, where D_m is the molecular diffusivity and l is a characteristic length-scale of the flow. The corresponding time for turbulent mixing is proportional to l/u, where u is the mean turbulent velocity fluctuation. The ratio of the former to the later time is $Re \cdot Sc$ where Re and Sc $(= \nu/D_m)$ are the Reynolds and Schmidt numbers, respectively. This product is large in most engineering applications (in gases mainly due to large Re), implying that in turbulent flow the mixing is dominated primarily by turbulence.

However, it was observed in the past that pulsatile injection, instead of continuous, enhances entrainment and mixing. In the review paper of Nathan et al. [27] mixing in jets is considered to be subjected to some means of jet exit nozzle pattern excitations. These excitations include acoustic excitation, flapping planar jet flows, and precessing round jet flows. The authors [27] note the fact that even relatively minor changes to the exit flow pattern of a round jet, through changes to the exit nozzle profile are found to propagate downstream into the far field. It is noted that increased large-scale mixing does not necessarily result in increased fine-scale mixing. The importance of generation of such structures on far field mixing is also questionable. However, in the situations considered here, the jet has limited length and hence we consider the near flow field, where the generated large scale structures have been proved to be beneficial for mixing, as is described below. By running the jet under unsteady conditions, improvement in terms of mixing can be attained. Borée et al. [4] carried out hot-wire measurements of a suddenly decelerating circular jet. They found large radial inflow of external fluid occurring during the phase of velocity decrease. This radial inflow causes enhanced entrainment. Additionally, a local negative energy production from the turbulent field to the mean field was found, which appears on the jet axis during the transient evolution. The effects of jet unsteadiness on mixing have been noticed some time ago. Joshi and Schreiber [18] studied impulsively

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started incompressible turbulent jet with emphasis on the transient phase. Favre-Marinet and Binder [13] showed that the entrainment of external fluid in a jet is increased significantly in the first few jet diameters by a large amplitude modulation (40 %) of the fuel injection velocity. However, these authors have shown that the developed zones of both pulsed and steady jets are very similar. Tanaka [34], Bremhorst and Hollist [7] measured the characteristics of air jets intermittently discharged into ambient fluid. This type of jet shows a much higher rate of entrainment than steady jets at the same mass flow do. In the LDV measurements of Bremhorst and Hollist [7] a pulsed subsonic jet with a significant no-flow period between pulses has been studied. It is shown that such a jet has much higher entrainment than steady or partially pulsed jets of the same mass flow. The effect of pulsations is observed up to distances of 50 nozzle diameters. Reynolds stresses are considerably larger than for a steady jet and are considered to be responsible for the increased entrainment. Kato et al. [19] showed, using pH indicators, that the mixing process in the jet is significantly modified by unsteady effects. The entrainment velocity depends not only on the jet velocity, but also on its time derivative. Similar findings of the effects of jet unsteadiness have been observed by Johari and Paduano [17] in their gravity-driven flow, in which they used dyed fluid from a vertical tube flowing into a large water tank. The measurements revealed that the portion of the unsteady jet, corresponding to the deceleration phase, dilutes more than the steady jet. By using acid-base neutralization reaction, it was shown that the jet mixes in a shorter distance than the steady jet. Modern diesel engines use so called common rail injectors. The injectors can be steered electronically with respect to duration and frequency of injection. Doudou [10] studied a single nozzle of such an injector. The axial velocity of the droplets was studied. The radial distribution of the normalized axial mean velocity was similar to that of the free gas jet within $r/r_{0.5}$ = 1.0–1.5 regardless of time ($r_{0.5}$ is the radius where the jet velocity attains half of the velocity at the center-line). The effects of intermittent injections on entrainment were not considered. Experiments and experience in the diesel engine industry indicated the benefits of staged/multiple injection of fuel. The initial purpose has been to generate stratified charges, but it has been observed that enhanced mixing is attained at the end of the injection pulse. A related engineering solution is using so called *rotating fuel injectors* (c.f. Choi et al. [9]). Borée et al. [4] measured the spatial and temporal evolution of axial velocities after a deceleration phase and showed that the region of increased entrainment grows in axial extent as it propagates downstream. Measurements carried out in recent years have shown that diesel jets experience greater mixing rates during and after a deceleration phase [26]. There have been some attempts to explain the observed effect of mixing at the end of injection. Pastor et al. [28] proposed a 1-D model for studying mixing of an inert diesel spray. The main assumptions of the model are the mixing-controlled hypothesis. The authors claim, that by making some further assumptions, the model would enable the estimation of the distribution of properties within the spray as well as the tip penetration. A more detailed analysis by Musculus and Kattke [25], Musculus [24] using also a 1-D model, indicates the formation of a so called entrainment wave. This entrainment wave propagates at a speed which is twice the speed of the (center-line) velocity of the jet. With the focus on the decelerating phase of a single phase jet, Hu et al. [16] performed three-dimensional simulations, which showed that mainly the large scale turbulent structures are responsible for the enhanced entrainment.

It is interesting to note that the effects of pulsed injection can also be observed in natural jets: there are objects in space, e.g. young stars, compact objects or galactic supermassive black holes, that generate astrophysical jets [3,14,30]. These jets consist of mass, momentum, energy or magnetic fluxes that are transported either through the interstellar or the intergalactic ambient medium. These jets have been modeled experimentally [2] and numerically [35]. Despite the fact that the properties of these kinds of jets are of a complete different parameter range than the above described fuel jets, similar features could be observed: the tail of the jet pulse moves with a different speed than the head. In this case, it was observed that the tail moves faster for jets that are denser than the ambient medium and slower for jets that are less dense than the ambient medium.

In the following we study numerically the behavior of an intermittent fuel jet into quiescent surrounding gas and analyze this behavior for different parameter set-ups; i.e. variations in the liquid/surrounding fluid density ratio, surface tension and injection repetition rate (relative to injection time). Enhanced mixing by intermittent injection is confirmed and explained by the axisymmetric vortex that is generated in the wake of the fuel jet whereby the speed at the tail increases relative to the head of the jet. The effect of intermittent injection of different frequencies on the atomization region, as well as on the spray region, is studied applying the VOF and the LPT method respectively.

2. Theoretical considerations

A typical injection scheme into a modern internal combustion engine includes several pulses. The intermittent injection has multiple functions. The first group of injections is to deliver the major portion of fuel used by the engine, whereas the later injections are aimed at improving emission formation properties of the engine. A late injection may also be added in order to allow enough hot fuel in the exhaust gas, so as to enable the re-burning of soot in the after-treatment system. As already mentioned above, partitioned injection has been found beneficial for the combustion process. Mixing may be regarded as the outcome of two (interlinked) processes. Larger scale vortices may transport species (scalars in the following) over longer distances in a given time, whereas smaller scale turbulence can account for local mixing that is mandatory for combustion and determines the formation of emissions. In the following, we study the contribution of different terms to the formation and strength of large scale vortices for different cases. Examining the vorticity (ω) transport equation (Eq. (1)),

$$\frac{\partial \omega_i}{\partial t} + u_j \frac{\partial \omega_i}{\partial x_j} = \underbrace{\omega_j \frac{\partial u_i}{\partial x_j}}_{\text{I}} - \underbrace{\omega_j \frac{\partial u_j}{\partial x_j}}_{\text{II}} - \underbrace{\varepsilon_{ijk} \frac{\partial (1/\rho)}{\partial x_j} \frac{\partial p}{\partial x_k}}_{\text{III}} + \frac{\mu}{\rho} \frac{\partial^2 \omega_i}{\partial x_j^2}, \tag{1}$$

shows the contribution to production through vortex stretching (I), the dilation term (II) and the so called baroclinic term (III). The vortex stretching term is essential for maintaining turbulence and in the enhanced mixing process found in non-circular exit nozzles, chevrons, and fluidic injections. The vortex stretching term is not directly related to the mechanisms of intermittent injection. Yet it plays an important role at the wake of the jet, where stopping the fuel injection leads to the formation of a shear-layer with a role-up of an annular vortex as a result. The baroclinic term (relates vorticity generation to the non-alignment of pressure and density gradients) may be important for non-isothermal cases. This situation may occur when density variations are formed by local heat-release (i.e. combustion) or transients of the type expected in our cases. The dilation term (ii) can be expressed, by using the continuity equation, as:

$$-\omega_j \frac{\partial u_j}{\partial x_j} = \frac{\omega_i}{\rho} \left(\frac{\partial \rho}{\partial t} + u_j \frac{\partial \rho}{\partial x_j} \right) = \frac{\omega_i}{\rho} \frac{D\rho}{Dt}. \tag{2}$$

As seen, the term depends directly on the temporal and spatial gradients of the density. Thus, for flows with large density non-uniformities there is a contribution to the generation/destruction of vorticity. It is also observed that large positive temporal density