Large-Eddy Simulation of Sprays - Connection of Droplet Size and Mass Loading Ratio to Turbulence Levels in Lagrangian Particle Tracking

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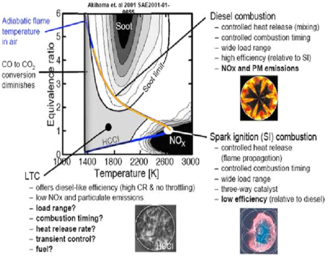
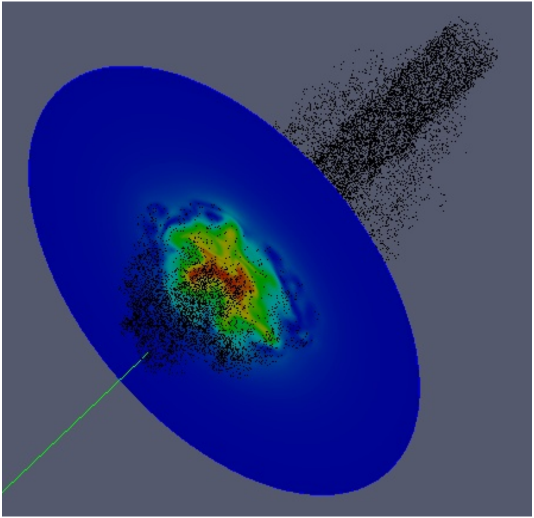
Background



- The fuel spray will influence the mixing process in diesel combustion.
- Large droplets produce turbulence and small droplets dissipate it.

- **How can we see/quantify this well-known phenomenon and it's consequences in a Large-Eddy Simulation of spray in a diesel spray type configuration?**
- Here we approach this question by studying **a model problem of spray - particle laden gas jet** - and test how small amounts of large particles and large amounts of small particles may affect the behaviour of the jet.

’A Particle Laden Jet’



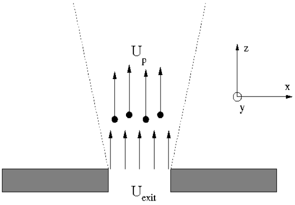
- Droplets enter a laminar gas jet that is randomly perturbed.
- The mass loading ratio $\varphi = m_{spray}/m_{gas}$ is an important parameter. $m_{gas} = 1.54 mg/ms$
- For each simulation constant size fuel particles with initial velocity $110 m/s$ enter a chamber in a jet with velocity $80 m/s$.

Assumptions

- We study a model problem of particle laden jet.
- Large-Eddy Simulation (LES) is used to simulate the gaseous phase.
- No subgrid scale model is used but instead a very fine grid is employed.
- Lagrangian Particle Tracking (LPT) is used to simulate the droplets.
- Droplets are spherical, point-like and non-deforming particles that do not break nor interact.
- Droplet momentum is tranferred directly to the resolved scale velocity field.
- The liquid volume fraction is small.

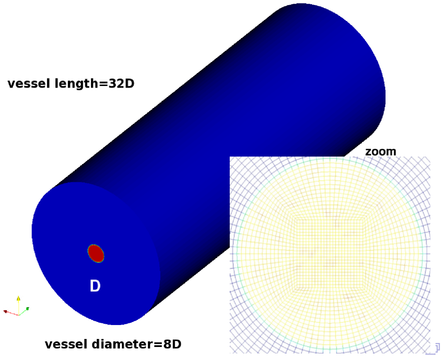
Simulation Setup 1/2

- **Influence of spray particles on turbulence:** study a subsonic jet at $Re = 10000$ with particles; sweep a range of particle sizes ($2 - 40\mu m$) and mass flow rates and measure turbulence levels in the flow field.



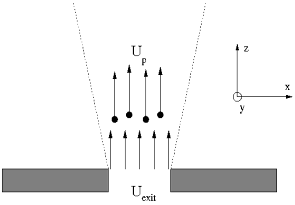
Simulation Setup 2/2

- 3M cell mesh. 250000 Lagrangian particles.
- Chamber is filled with N_2, $p = 5bar$, $T = 293K$.
- Parallel simulations carried out with OpenFOAM-1.3, simulation time = 1-2 days on 24 processors.
- Injection time $\tau_{inj} = 1ms$ and jet diameter $D = 2mm$.

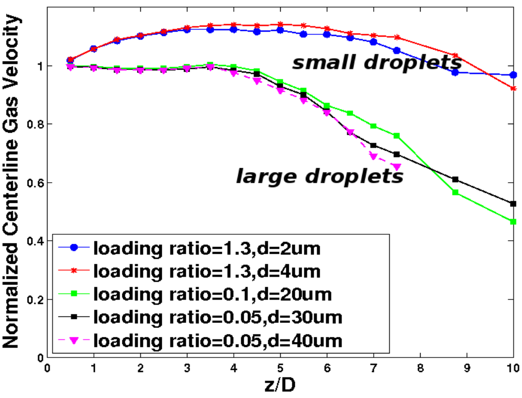


Results

- Jets and sprays are free shear flows in which turbulence is produced (i.e. transferred to velocity fluctuations from the mean flow) mainly in the shear layer.
- Thus we focus our attention to the spray axis and shear layer.

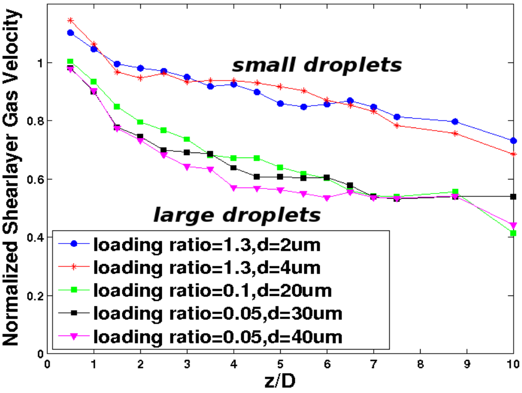


Mean Gas Velocity in the Centerline



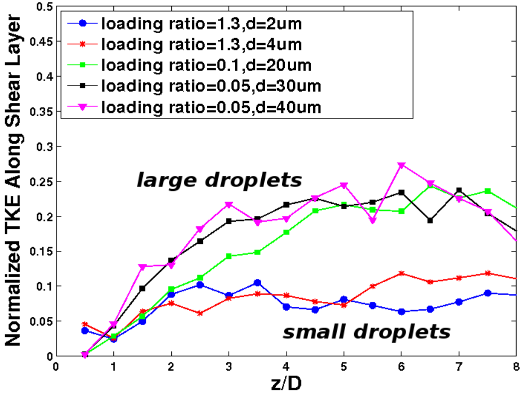
- At all mass loadings and drop sizes *potential core* is observed.
- Small drops loose momentum efficiently and raise gas velocity at centerline in the core region.
- For large drops the core length is about $4D$ similar to 'normal' jets.

Mean Gas Velocity in the Shear Layer



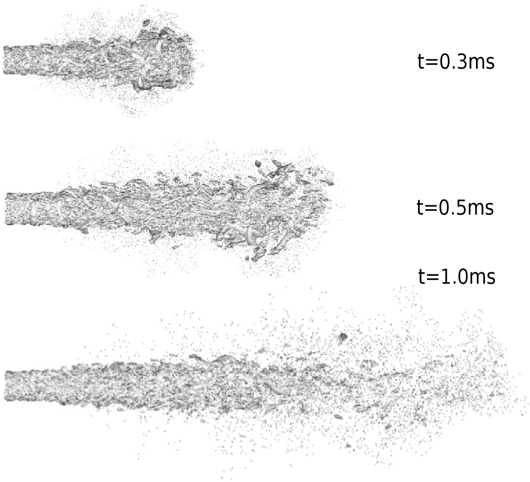
- The mean shear layer velocity is always decreasing.
- This means that in the near-field along the shear layer energy is transformed into turbulent kinetic energy from the mean flow.
- For the largest droplets the decrease in mean flow is most rapid.

Turbulent Kinetic Energy Along the Shear Layer

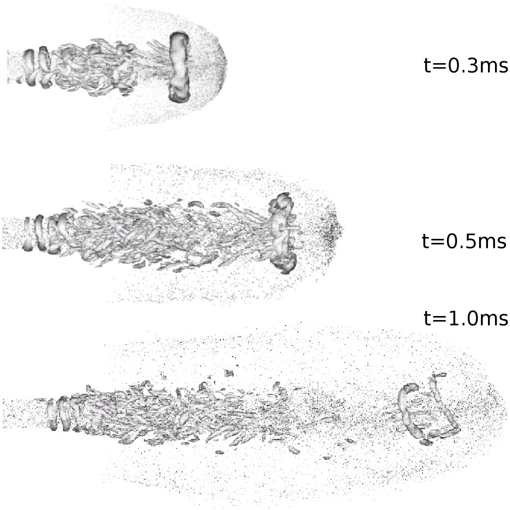


- The figure quantifies the fraction of tke to mean kinetic energy.
- In the case of large droplets kinetic energy is very efficiently transformed into fluctuation with the trend being increasing with the drop size.
- In the case of excessive amounts small droplets energy is not transmitted efficiently into fluctuations.

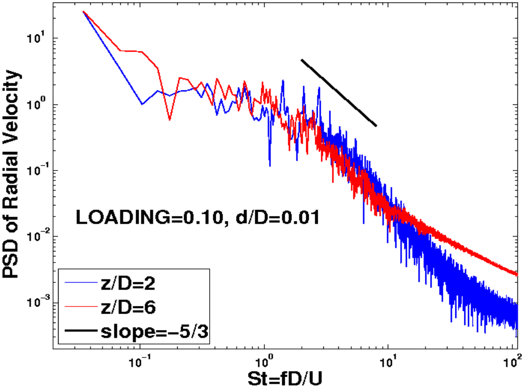
No Evident Flow Structures Appear if Comparable Mass Loadings of Small Drops are Present: $\varphi = \mathbf{1.3}$



Large Coherent Flow Structures Appear if Large Drops are Present: : $\varphi = \mathbf{0.1}$

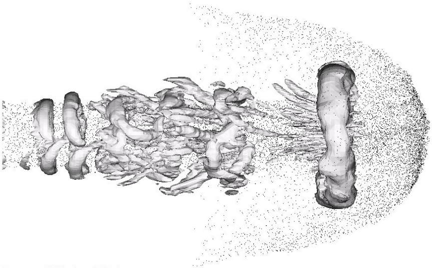


Example of Shear Layer Spectrum for Large Particles

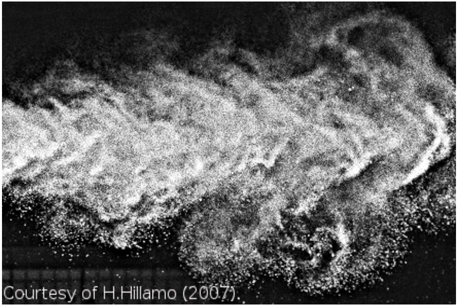


- The Kolmogorov slope seen from the spectra.
- The natural frequencies of the jet observed at given Strouhal numbers.
- Enhancement of high frequencies towards downstream.

LES and PIV Support One Another



Courtesy of V.Vuorinen (2007)



Courtesy of H.Hillamo (2007).

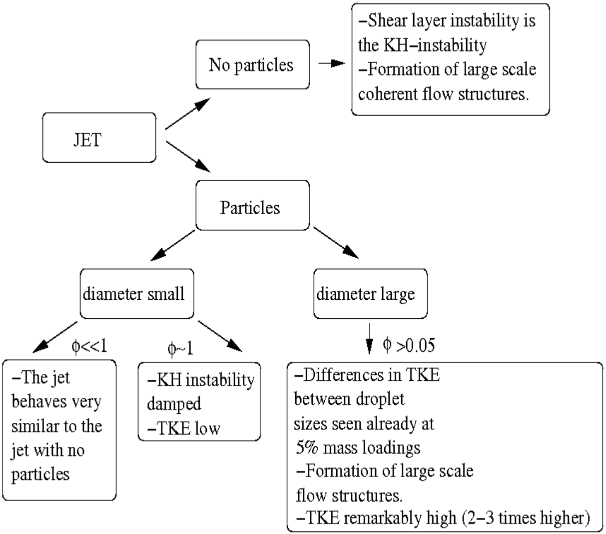
LEFT:
-LES+LPT model on non-atomizing $d = 20\mu m$ droplet-vortex interaction.
-Large coherent flow structures are seen as in ordinary jets.

RIGHT:
-A PIV of diesel spray visualizes how atomizing droplets interact with large vortices.
-Coherent structures observed.

Explanations

- Small droplets respond quickly to changes in the flow (they have small Stokes number). Thus they dissipate eddies by making the gas effectively heavier.
- This prevents formation of large scale coherent eddies by damping out the Kelvin-Helmholtz instability that is responsible for the shear layer instability.
- Large droplets interact essentially only with large scales - they do not dissipate small scale turbulence.
- The KH-instability of the jet may form if large scale droplets are present.

Map of the Trends for a Jet at Re=10000



Summary

- LES+LPT of non-atomizing spray has been carried out.
- It was shown and *quantified* within the model in terms of TKE that large droplets produce turbulence and small droplets dissipate it.
- Connections to formation of large scale structures was pointed out.
- LES+LPT and PIV support one another in building ’the big picture’.
- Our future studies include sprays with droplet size distribution, sprays with secondary atomization, studies of scalar mixing, evaporating sprays etc.
- THANK YOU FOR YOUR ATTENTION! QUESTIONS?

Large-Eddy Simulation of Sprays - Connection of Droplet Size and Mass Loading Ratio to Turbulence Levels in Lagrangian Particle Tracking

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Abstract

In this work a particle laden jet at $Re = 10^4$, $Ma = 0.3$ is studied using the combination of Large-Eddy Simulation and Lagrangian Particle Tracking. The method serves as a synthetic model of *fully atomized* liquid spray that enters a chamber filled with gas through a hole with diameter D. The value of D is much larger than typical injector diameters. The specific feature of this model is that it provides a simple environment for studying phenomena inherent to spray-originated turbulence such as particle-turbulence interaction, formation of large scale flow structures and atomization $without$ the modeling difficulties near the physical nozzle where the used method is strictly speaking not valid yet commonly used in spray simulations. It is noted that in the near-field region the system responds to variation in particle size and mass loading ratio in terms of production of turbulent kinetic energy. The results show that these parameters may have a central role regarding the production and dissipation of turbulence within ten jet diameters in the near-field region. Relation of the afore-mentioned phenomena to the formation of large scale structures and spray shapes are demonstrated and discussed.

Keywords: Large-Eddy Simulation; Lagrangian Particle Tracking; Turbulence Production and Dissipation; Mixing

1 Introduction

Turbulent multiphase flows constitute a group of systems that are far from trivial in comparison to 'ordinary' single phase flows. Namely, presence of discrete particles or droplets, several continuum phases or even chemical reactions in turbulent environment may provide such additional degrees of freedom that can strongly affect the flow behaviour. Examples of complex multiphase flow applications vary from nuclear reactors, medical inhalator, paint and coating sprays to combustion environments including chemically reacting flows in gas turbine engines and fuel sprays in diesel engines.

The main, final object of interest in this work is the diesel fuel spray in direct injection combustion engines. A typical diesel spray consists of large numbers and broad size ranges of liquid fuel droplets up to $100\mu m$ in size. The liquid fuel is atomized by extremely high injection pressures of order $10^2 - 10^3 MPa$ through a narrow nozzle. Typical nozzle diameters are within the range $150 - 200\mu m$. Near the nozzle the fuel volume fraction is of order unity and the spray appears as a complex mixture of ligaments, droplets and gas. However, in the far-field region the volume fraction becomes small due to spreading of the spray and the spray consists more and more of identifyiable droplets.

Formation of diesel spray is a very complex phenomenon that, in practical applications, is strongly affected by initial turbulence conditions including large scale turbulence structures such as cylinder swirl, droplet evaporation in high temperature conditions, cylinder and injection pressures as well as the way in which the spray is injected through the injector. Due to large scale fluctuations the spray behaviour may vary from one combustion cycle to another. Thus, full characterization of diesel sprays is very difficult if not impossible in other than mean time and global terms including average spray penetration and width related issues. Another typical characterization is to only look at the overall performance of an engine such as average pressure trace, engine efficiency and levels of emissions (see e.g. Wahlin [2007]). However, increased requirements to reduction of emissions and investments on development of alternative fuels feed the continuous interest to gaining more and more profound understanding on the underlying fundamental processes that take part in diesel spray formation. Some of the previous works on spray formation and related phenomena have been discussed by Pilch *et al.* [1987], Faeth [1996] and Marmottant *et al.* [2004] and in the citations therein.

A continuous trend in combustion research is to understand the role of effective turbulent mixing. This has resulted in numerous publications related to free shear flows. From the viewpoint of spray research especially the studies that are related to jets are interesting. Some recent studies on turbulent round jets include those of Burattini *et al.* [2004a], Burattini *et al.* [2004b] and Örlü [2006]. In the context of diesel sprays the interesting question is related to achieving optimal mixing *by the spray* in premixed combustion since NOx and soot emissions may be drastically reduced if the combustion takes place in low temperature conditions at optimal air to fuel ratios. Since the spray itself is one of the few factors that can be directly controlled in a diesel engine, the focus of several researchers on spray formation seems reasonable. Some recent experimental studies of fuel droplets in a jet include atomization studies of droplets in a jet crossflow by Park *et al.* [2006] and droplet-gas correlation studies in a jet by Ferrand *et al.* [2003].

In general, the interaction between a particulate and the carrier phases may be one- or two-way momentum coupled or four-way coupled in which case also the particle-particle interactions are important. In this work only 2-way coupling i.e. momentum exchange between the gas and particles is considered. Then, as suggested by Kenning *et al.* [1997] the coupling between the phases is as in any 'generic' particle laden flow and the production of turbulence may be divided into inherent production by Reynolds stresses and mean gradients as in single phase case and production of turbulence by the particles. Similarly, two factors contribute to the dissipation of turbulence i.e. viscous dissipation rate of turbulent kinetic energy and dissipation caused by the particles. Recent experimental studies considering particle-turbulence interactions include those of Righetti *et al.* [2003] and Poelma *et al.* [2006].

Turbulent flows including those with particles have been studied also by means of numerical simulations. During the past decade the Large Eddy Simulation (LES) method has been applied to many kinds of turbulent flows together with Lagrangian Particle Tracking (LPT) Monte-Carlo method that provides means for solving the discrete particle phase. Sankaran *et al.* [2002] and Apte *et al.* [2003a] have applied the LES-LPT technique in the context of swirling flows with spray whereas Vinkovic [2005] used LES-LPT to simulate droplet dispersion for inhomogeneous turbulent wall flow. The technique has also been applied in the context of diesel spray simulation by e.g. Apte *et al.* [2003b] and recently by Hori *et al.* [2006]. In the context of jets without particles the method has been used by Olsson *et al.* [1995] and recently by Hällqvist [2006].

In this paper a jet that is loaded with particles is studied using Large-Eddy Simulation (LES) and Lagrangian Particle Tracking (LPT). This setup is chosen in order to serve as a *synthetic model* of diesel spray i.e. fuel droplets in turbulence. The advantage of this specific model is that many of the near-nozzle modeling difficulties in the dense spray region are overcome. The model is assumed to be helpfull in understanding spray-originated turbulence since studying the particle laden jet (PLJ) with LES-LPT provides several physical elements that exist also in real diesel sprays. Jets, similar to sprays, also belong to the generic class of free shear flows that are free from wall interactions and in which the production of turbulence is strongly localized to the *shear layer* in the near-field region. Most importantly, jets have been rather extensively studied in the past so the theory of jets provides a solid base to look at the problem of diesel spray formation.

The earlier computational and experimental studies have not only shown that particles influence turbulence levels of the carrier phase but also shown that there is quite little understanding on the underlying phenomena to date. However, LES has been used in the past in particle laden flows together with LPT and very promising results have been achieved supporting further development of the method (see e.g. Apte *et al.* [2003a], Hori *et al.* [2006], Vuorinen [2007]). The experimental and computational studies on jets have shown that for any LES computation to capture physics of jets, including large scale coherent flow structures and turbulent spectrum, fine spatial resolution within the shear layer is required. In the earlier LES-LPT studies of sprays this has seldom been possible due to practical reasons and modeling of the subgrid scales has been employed instead. However, the earlier studies (see e.g. Hällqvist [2006] and Vuorinen [2007]) support implicit filtering instead of explicit subgrid scale modeling in jet simulations. This requires fine spatial resolution and is our approach to the PLJ problem.

The primary purpose of this paper is to demonstrate certain situations that can be achieved within the model. These situations are related to connection between droplet sizes, mass loading ratios and turbulence production as well as formation of large scale flow structures. This study serves as a prelude to a series of studies that aim to developing the LES-LPT combination to a tool that can be used for gaining realistic information about turbulence formation, atomization and mixing in diesel engines and other such spray applications where the method as such applied in the near-injector region is non-physical.

2 Problem Description

2.1 Governing Equations

The dynamics of a particle laden compressible jet is described by the compressible, full Navier-Stokes equations (NS) with a spray momentum source term:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial}{\partial x_j}(-p\delta_{ij} + \sigma_{ij}) + \mathcal{M}_{spray} \tag{2}$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial (\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}(\sigma_{ij} u_i) + \frac{\partial}{\partial x_j}\Big(\lambda \frac{\partial T}{\partial x_j}\Big) \tag{3}$$

where

$$\mathcal{M}_{spray} = C_D(u_i - u_{p,i})|u_i - u_{p,i}|\delta_{r,r_p} \tag{4}$$

is the spray momentum source term at point r that is activated by the delta function and the viscous stress tensor is defined as

$$\sigma_{ij} = \mu\Big(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\Big) - \frac{2}{3}\delta_{ij} \cdot u_{ii}. \tag{5}$$

Here the subscript p stands for a 'particle' and u for gas or particle velocity. For round particles the following correlation formula for the drag coefficient is assumed to hold

$$C_D = \begin{cases} \frac{24}{Re_p}\Big(1 + \frac{1}{6}Re_p^{2/3}\Big) & Re_p < 1000 \\ 0.424 & Re_p \geq 1000. \end{cases} \tag{6}$$

where Re_p is the particle Reynolds number (see e.g. Amsden *et al.* [1989]).

In Large-Eddy Simulation the NS-equations (1)-(3) are spatially filtered and the resulting subgrid scale (SGS) terms are modeled. During the past decade different types of $explicit$ SGS-models have been developed in order to recover the actions of the SGS-processes including viscous dissipation, production of turbulence by the SGS Reynolds stresses and energy back-scatter (see e.g. Fureby *et al.* [1996]). In this work, however, we consider *implicit filtering* and solve the NS-equations (1)-(3) in a fine grid.

2.2 Computational Setup

Figure 1 shows a schematic illustration of the computational setup and the computational mesh. The setup consists of a round jet with diameter $D = 2mm$ that enters a cylindrical chamber with diameter $8D$ and length $32D$. The chamber is filled with nitrogen that is initially pressurized to the pressure of $5\ bar$. The pressure in the chamber is $T_g = 293K$. The inlet velocity profile is a top hat profile that is perturbed with slightly time-correlated and uniformly distributed noise. Spherical, non-deforming particles are introduced to the chamber by randomly choosing an initial position from the first two cell layers within the jet region at the inlet. The entraining jet is simulated at the inlet diameter and gas velocity based Reynolds number of 10^4. The Mach number at the inlet is about 0.3. In this work the inlet gas flow condition is fixed to have a mean of $U_{exit} = 80m/s$ and a low amplitude white noise component of $\delta U_{exit}/U_{exit} = 5\%$. This corresponds to an average gas flow rate of $\dot{m}_g = 1.54 \cdot 10^{-3} kg/s$ through the inlet. The initial velocity of the particles is $U_p = 110m/s$ and the density of the particles is $\rho_p = 830kg/m^3$. The total simulation and injection time is $\tau_{inj} = 1.0ms$.

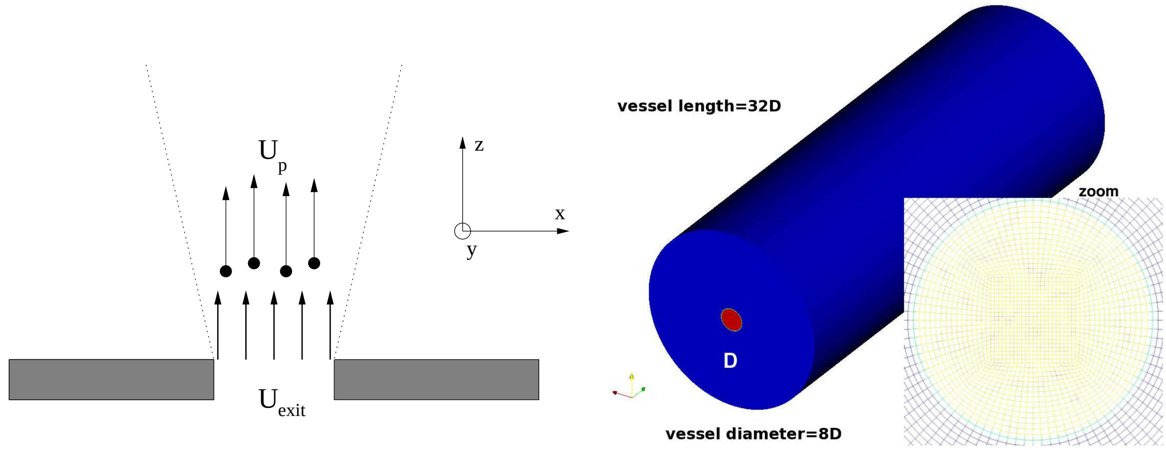

Figure 1: **Left:** A sketch of the jet geometry. Dashed lines outline the jet spreading angle and the location of the shear layer. The black spheres represent the droplets. **Right:** The computational mesh.

The direction of entrainment is $+z$ and the inlet lies in the plane $z = 0$. The inlet center is at $(x, y) = (0, 0)$. The width of the domain has been found to be wide enough so that the flow does not touch the walls of the container.

The mesh contains about 3M cells. We noted that the production scales were not captured if there were only 200 grid points in the streamwise direction. With 250 streamwise points the solutions were still quite dissipative. When increasing the mesh resolution to 300 we noted that the production and dissipation length scales were adequately captured by the algorithm. The domain was decomposed in the streamwise direction onto 24 processors. With this decomposition each simulation took about 30 clock hours. Further details about the simulations are found in Vuorinen [2007].

2.3 Physical Situation

The model considered here is associated to a physical situation where hard and spherical particles enter a jet. The mass loading ratio φ is defined as the spray and gas mass injection rates $\varphi = \dot{m}_{spray}/\dot{m}_g$. If $\varphi \gg 1$ the flow is highly dominated by the particle phase and four-way coupling needs to be assessed. Only situations where $0.05 \leq \varphi \leq 1.3$ will be considered here corresponding to low volume fractions of less than 1%. A dimensionless number that relates the characteristic particle timescale to the flow timescale (specified as a ratio of length and velocity scale) is the particle Stokes number St_p defined as

$$St_p = \tau_p \frac{\delta}{U}. \tag{7}$$

It is expected that the particles having $St_p \ll 1$ follow the fluid whereas particles for which $St_p \sim 1$ will interact with the fluid by momentum exchange. Particles for which $St_p \gg 1$ will travel quite independently of the surrounding eddies. As noted by Salewski *et al.* [2005], in turbulent sprays a range of Stokes numbers appears. This is the case even in monodisperse sprays as here. As noted by Sankaran *et al.* [2002], depending on the spatial location, particles can behave as 'large' or 'small' particles. Thus, in the presence of a small eddy, particles with small diameter may behave as 'large' particles inside a larger eddy.

3 Methods

3.1 The Numerical Scheme for the Continuum Phase

The simulations were carried out using the OpenFoam-1.3 open source CFD-code that uses the control volume formulation as a basis for most of the solvers. The code is developed and provided by OpenCFD Ltd [2007]. The code also has a Lagrangian library for spray and other multiphase flow calculations. For our future research purposes, the flow solver was chosen to be a pre-conditioned compressible LES solver using a PISO based pressure correction method where the Poisson-equation is solved for the pressure. The number of corrector steps was set to the value of 2. The solver is second order accurate in space and first order accurate in time. The convection term was discretized using a scheme that was given a formal second order accuracy. However, asymptotic grid study was not carried out. The Navier-Stokes equations were advanced with the first order implicite Euler time integration. Due to the first order accuracy the maximum Courant number in the system was made to be as low as 0.1. This condition was met near the jet inlet. Globally, the Courant numbers are smaller than that. Maximum Courant numbers that were higher by factor 1.2 were noted to lead to significant convergence problems especially for the Poisson solver. If the maximum Courant number in the system was higher by factor 1.4 the algorithm became unstable.

3.2 Lagrangian Particle Tracking

In Lagrangian Particle Tracking the equations of motion for the particle phase are solved. Since the number of physical particles can often be large, in LPT these are gathered into statistical units called parcels. Each parcel contains a certain number of physical particles that are assumed to be of same size here. The number of parcels is kept as a constant and it is set to the value of $N = 250000$. This value was chosen primarily due to three reasons. First, adjacent computational cells will be coupled since there will be of the order of one parcel/cell in the near-field of the jet. Second, higher parcel numbers were noted to cause load balance problems in the parallel computations. The third reason is related to the situation where the particles are large in comparison to the grid spacing: although computational resources would allow tracking each of the particles separately for a small φ, the coupling between the phases would be unphysically strong. Thus, keeping the number of computational parcels higher than the number of physical particles is required in order to stabilize the computations and keep the local error low. In this case each parcel carries a fraction of a physical droplet. This can be considered to be a consistent approach with LES: instead of following a point particle also the particle position is average within the filter width.

The particle equations of motion were discretized in a semi-implicite manner and five subiterations within the timestep were carried out on each time step for the particle phase in order to stabilize the computation as implemented in the Lagrangian library. In principle, during a computational timestep a particle may cross several cells and the lost momentum is transferred to the source term of the gas phase. However, in these simulations the gas phase Courant number was low and the particle velocity of the same order as the gas velocity so that typically particles do not cross more than one cell during a timestep. The gas velocity is interpolated from the neighbour cell faces to the particle positions. In contrast, the momentum source term in the gas phase equations is modeled by directly adding the momentum lost by the particle to the cell it resides in. The particles couple directly to the momentum equation 2 by the source term .

4 Results

4.1 Basic Picture of the Flow Fields

Figures 2 and 3 show examples of two particle clouds, the former with small particles and high loading ratio and the latter with large particles. As seen from the left columns of the Figures, small particles are dispersed into a uniform cloud from the jet region starting $2-3$ jet diameters downstream by turbulent fluctuations whereas the large particles will head straight forward. However, the large particles having larger Stokes number loose their momentum fast in the tip of the spray. Thus, the large particles form a cloud that resembles an opening umbrella whereas the small particles form a more uniform dispersed cloud.

The right columns of the Figures 2 and 3 show how the constant isosurface of Λ_2, a quantity that identifies vortex cores from the topology of a flow field, develops in time. In Figure 2 the flow field looks rather uniform and no special large scale flow structures are observed. In contrast, in case of large droplets the situation is very different. As Figure 3 shows at early times vorticity is formed in the shear layer. A clear indication of this are the ring vortices that are formed around the jet. Complicated interactions lead to vortex merging around $z/D = 3-4$. It is clear that in the tip of the jet a large scale ring vortex structure is formed. As the axi-symmetric vortex changes character, axially oriented vortices are formed. The main difference between a particle free jet and the cases considered here is the relatively quick break down of the large scale vortices.

The drastical differences between these two simple examples demonstrate that global features of sprays are governed by two factors: particle size and mass loading. From the viewpoint of the practical application, a diesel spray, this kind of observations might be crucial since the global, large scale flow structures will have a strong effect on entrainment and mixing rates. In real situations the spray would contain a particle size distribution. These examples then illuminated

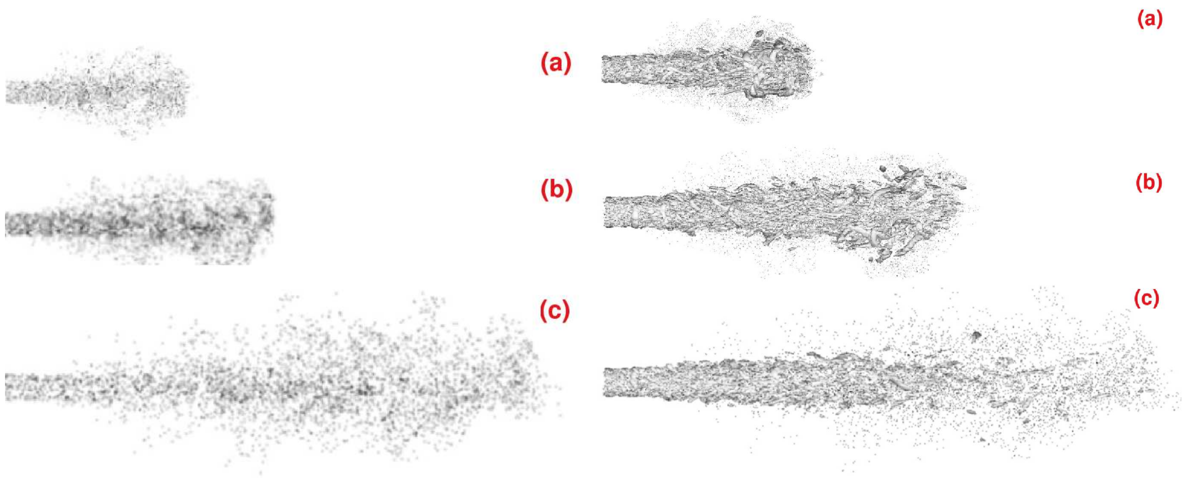

Figure 2: **Left:** Spray evolution with small particles ($d/D = 0.001, \varphi = 1.3$). (a) time=0.3ms (b) time=0.5ms (c) time=1.0ms. **Right:** Evolution of the isosurface of Λ_2. (a) time=0.3ms (b) time=0.5ms (c) time=1.0ms.

the fact that in practice the global spray features such as shape may be formed as a superposition of 'jets' with different amounts of large and small particles.

4.2 Velocity and Turbulence Levels in the Flow Field

Next, we consider the mean velocity and turbulence levels along the jet axis and the shear layer. The normalized mean and axial velocity with different particle sizes and loadings is shown in Figure 4.

In the proximal part of the jet, with large particles the axial velocity remains constant until the end of the potential core around $z/D = 4$ where the velocity starts to decrease as a result of the expansion of the jet shear layer. In the case of small particles and high mass loading ratio the mean axial velocity first increases and then decreases. This makes the effective potential core longer and thus turbulent flow is not observed until far downstream. Figure 4 depicts the mean velocity along the shear layer. For all the studied cases the velocity is decreasing. Near the inlet the mean velocity gradient is much larger for the large particles than for the small particles. This is related to higher level of production of turbulence.

In LES the turbulent kinetic energy can be estimated directly from the variance of velocity time series at a given point. In Figure 5 the mean turbulent kinetic energy normalized with the local mean kinetic energy is shown. As can be seen large particles will remarkably increase the turbulence levels in the shear layer whereas high loadings of small droplets will keep the turbulence levels down. In the case of large droplets this trend is also reflected to the jet axis whereas in the case of small droplets the turbulence levels stay low both in the shear layer and the jet axis. Although the statistics that was used to collect the data in Figures 4 and 5 was not adequate (the period of averaging was at most tens of eddy-turnover times, in general the situation is transient and ensemble averaging should be considered etc) the trends and correlations seem clear (i) the larger the

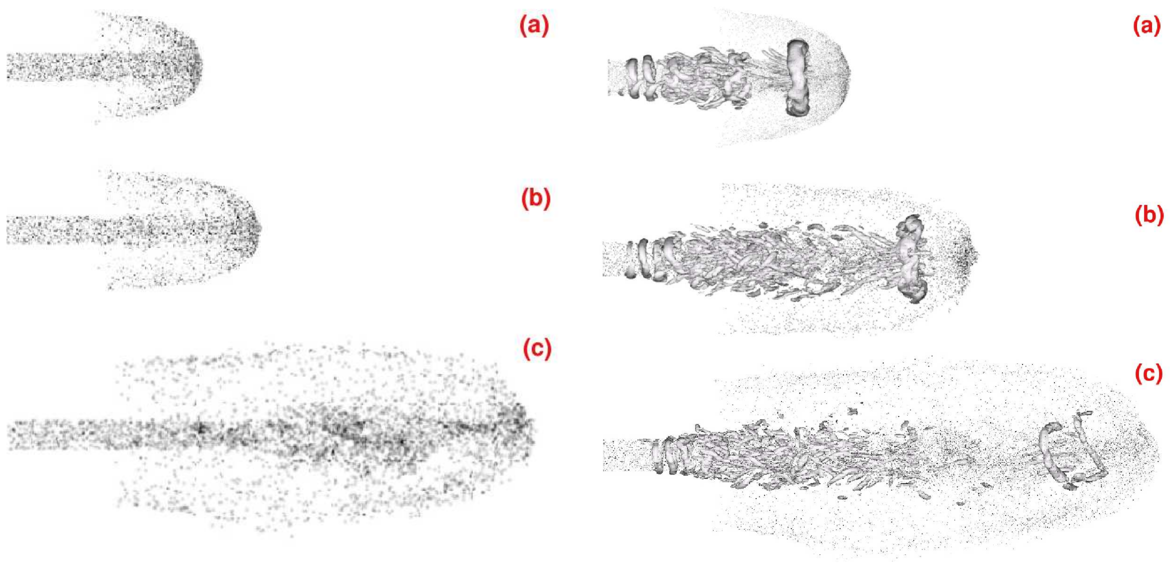

Figure 3: **Left:** Spray evolution with large particles ($d/D = 0.01, \varphi = 0.1$). (a) time=0.3ms (b) time=0.5ms (c) time=1.0ms. **Right:** Evolution of the isosurface of Λ_2. (a) time=0.3ms (b) time=0.5ms (c) time=1.0ms.

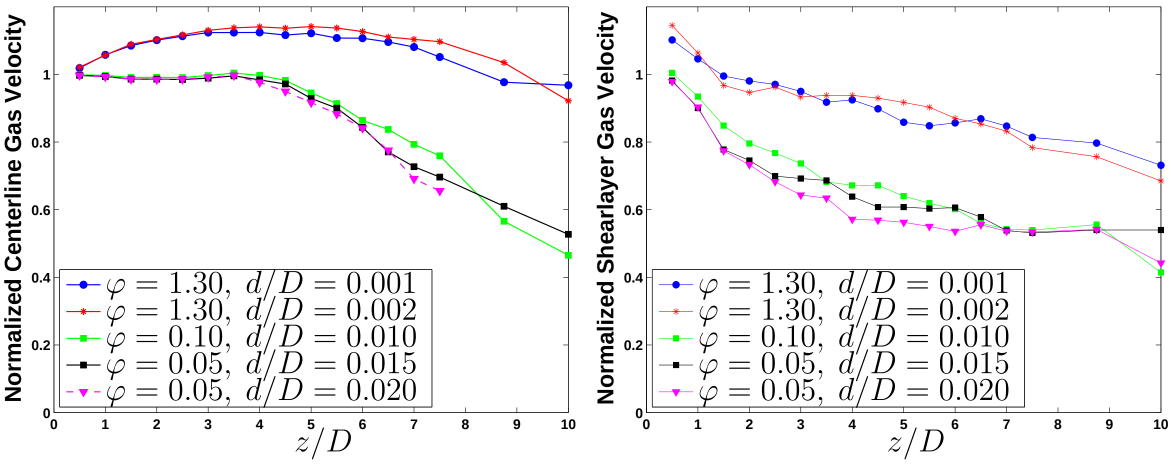

Figure 4: **Left:** The mean velocity along the jet axis. The potential cores for jets with large particles ends around $z/D = 4$. For small particles the core extends longer downstream. **Right:** The mean velocity along the jet shear layer.

droplets are the more turbulence will be produced and (ii) high loadings of small droplets may dissipate turbulent fluctuations and thus have an adverse effect to the production of turbulence and hence mixing.

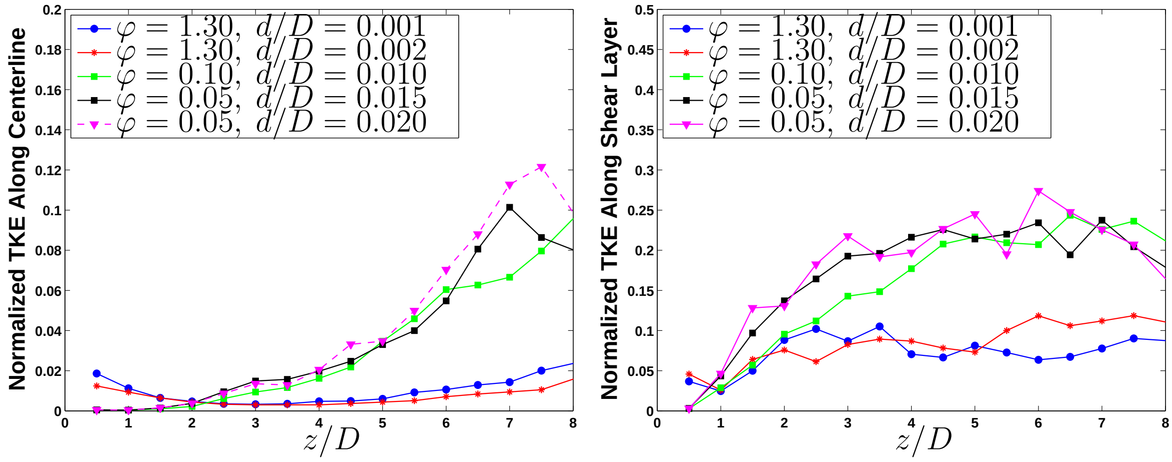

Figure 5: Turbulent kinetic energy normalized with the local mean kinetic energy. **Left:** Taken from the jet axis. **Right:** Taken from the shear layer.

5 Conclusions

In this work the LES of a jet loaded with particles has been considered. The simulation results showed how the turbulence levels in the shear layer are strongly affected by the presence of particles. The turbulence level in the shear layer depends on the particle diameter so that the large particles could contribute to the production of turbulence whereas high loadings of small particles will have a negative effect into the production process and they will dissipate spectral energy from the high frequencies. Thus the gas starts to behave as a heavier fluid in the case of small droplets.

An issue that was noted in this work was the connection between turbulence dissipation by small particles and large scale vortex structures. This observation is especially interesting in the case of the practical application, i.e. the diesel spray since the observation puts overly primary atomization of droplets into a questionable position: having too large amounts of small droplets at critical places could have an adverse effect on the formation of large scale structures, production of turbulence and thereby mixing. In contrast, having reasonable amounts of large droplets properly distributed in the near field of a spray jet could have a positive overall effect on the formation of large scale flow structures and production of turbulence. This kind of observations could have interesting consequences to fuel property related issues such as surface tension and viscosity which are coupled to primary and secondary breakup.

Our future work includes similar studies on different particle size distributions, studies on passive scalar mixing, studies on droplet atomization, studies on evaporating and combusting sprays. In our opinion continuous development of numerical models with LES+LPT offer a very reasonable means of understanding sprays.

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