Dispersion and Growing of Ice Particles in a Turbulent Exhaust Plume

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ABSTRACT: Contrails may have an impact on cloudiness and may affect the Earth's radiative budget balance. In order to better understand their formation, preliminary study on the dispersion of gas and particles (soot and ice) in the exhaust jet and on their modification by wake processing has been performed. This work is focused on the 3D numerical simulation of dynamics and microphysics in a near-field of an aircraft wake. Large Eddy Simulations have been carried out at realistic flight Reynolds number to evaluate the effects of turbulent mixing and wake vortex dynamics on gas and particle mixing.

1 INTRODUCTION

Aircraft exhaust contains products resulting from combustion in gas or solid phase. Ice particles that mainly nucleate on exhaust soot and volatile aerosols can lead to the formation of contrails which may have an impact on cloudiness and may affect the Earth's radiative budget balance. In order to better understand the formation of contrails, fundamental studies on the dispersion of gaseous and particles (soot and ice particles) in the near field of an aircraft wake and their modification by plume processing are necessary.

In this article a condensed survey is given on unsteady numerical simulations of the plume processes that were in part already described in previous publications. A detailed description of the different numerical approaches is given in the works of Ferreira Gago *et al.* (2002), Paoli *et al.* (2002) and Paoli *et al.* (2003).

The numerical simulations of the flow are based on the use of 3D temporal DNS/LES of the compressible Navier-Stokes equations. In the LES approach, these equations are filtered in order to reduce the number of scales to be solved. Among the various subgrid scale viscosity and heat flux models used in the LES works, the compressible version of the hybrid Smagorisky model (linear combination of the Smagorinsky and the similarity model) and the Structure Function model displayed the best performances, especially when dealing with the turbulent stresses and the turbulent heat flux (Ferreira Gago et al., 2003; Métais and Lesieur, 1992). The LES equations are solved by using a sixth-order compact scheme in space and the time marching scheme is a three-order Runge-Kutta algorithm.

In the present work we have focused on the simulation of contrail formation and early-stage evolution in the near field of an aircraft wake (i.e. up to a few seconds from the emission time).

Eulerian two-fluid models of particle-laden flow are based on a volume averaging approach, describing macroscopic properties (phase volume fractions, average solute mass fractions and velocities…) of a two-phase mixture. This work uses the alternative Lagrangian particle tracking approach. It seems more suited to the future modeling needs of microscopic phenomena occurring in the exhaust jet and vortex wake of an aircraft (activation of soot, ice crystal condensation and co-

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agulation of volatile aerosols). Due to the small size of the soot-ice particles (from tens of nanometers to a few microns), their relaxation time is negligible compared to the characteristic times to the filtered variables. This allows them to be treated as a tracer. In addition due to the high number density (about 2.5 10^{11} m^{-3}, Karcher *et al.,* 1996), we can carry only packets of particles where each one containing a large number (10^{+6}) physical particles. In the coupling terms which are involved in the LES equations, we only consider the mass exchange, i.e. vapor condensation on the soot particles (so the thermal coupling will be neglected).

2 AIRCRAFT PLUME DYNAMICS

2.1 *Jet/vortex interaction*

In the near field of the aircraft wake, the exhaust jets of the engine are entrained into the counter-rotating wingtip vortices. The entrainment process and the associated turbulent mixing are complex and it is convenient to identify two overlapping regimes (Garnier *et al.*, 1997): the jet and interaction regimes. The first one is that of usual co-flowing jets and it scales with the jet diameter. Later, the interaction of exhaust jet and the wake vortex characterizes the second regime. The convection and shearing processes associated with the tangential velocity field of the trailing vortex strongly affect the exhaust jet dispersion. In the present numerical study, these two regimes are modeled sequentially. The axial length of the domain of 6 nozzle radii corresponds to twice the wave length of the maximum growth rate of the first azimuthal instability of a spatially evolving jet (Michalke and Herman, 1982). An instable nozzle outlet velocity profile is prescribed. When the jet simulation has reached an age that corresponds to a downstream distance of 0.5 wingspans, the cross section of the domain is enlarged and a Lamb-Oseen vortex is superimposed on the flow field at a distance of 14 vortex core radii from the jet center.

An experiment detailed in Brunet *et al* (1999), delivers a database that can be used for improving the numerical simulations. The wake of a generic model corresponding to a rectangular plan form NACA0012 equipped with two heated jets is investigated. The experimental results comprise mean and fluctuating velocity fields (measured with a LDV system) and mean temperature field (measured with thermocouples). Unsteady aspects of the flow are also described by means of hot wire measurements. The experimental results show that the flow does not affect the engine jet behaviour until a downstream distance of 0.5 wing spans. For modern large transport aircraft, the characteristic size of the jet regime is of the order of 1-50 diameters of the nozzle exit, while the deflection regime, scaled to the wingspan, extends downstream of the aircraft to a distance of about 0.5-10 wingspans.

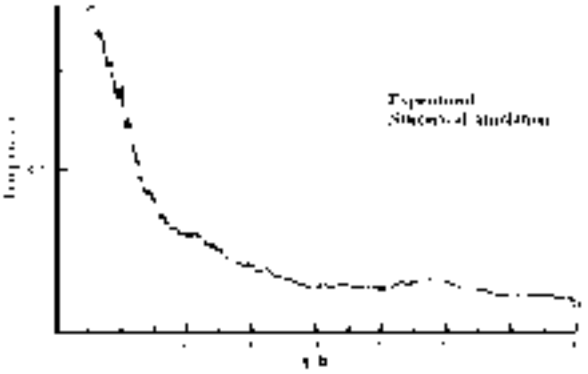

Figure 1. Downstream evolution of the dimensionless temperature T/Tj, where Tj is the nozzle exit temperature. Comparison with experimental data.

Thereafter numerical results are compared with the experimental database, and an example of the results is shown in Figure 1 where the downstream variations of temperature T peak values are represented. The temperature evolution throughout the near field of the wake as obtained from numerical predictions is in agreement with the experimental results.

2.2 *Gaseous exhaust mixing*

In order to illustrate the entrainment and mixing processes of the gas exhaust, we examine the contours of axial vorticity and species concentration (defined as a passive scalar concentration) as shown in Figure 2. The turbulence induced by the exhaust jet is wrapped around the wing-tip vortex. This interaction results in the generation of small scale motions close to the vortex core and rearranges to coherent secondary vorticity structures (but now ring shaped) of opposite signs. The region very close to the core retains its positive axial vorticity contours, but they are no concentric anymore. At this stage, one can see that the gaseous exhaust dispersion is mainly controlled by these new organized structures.

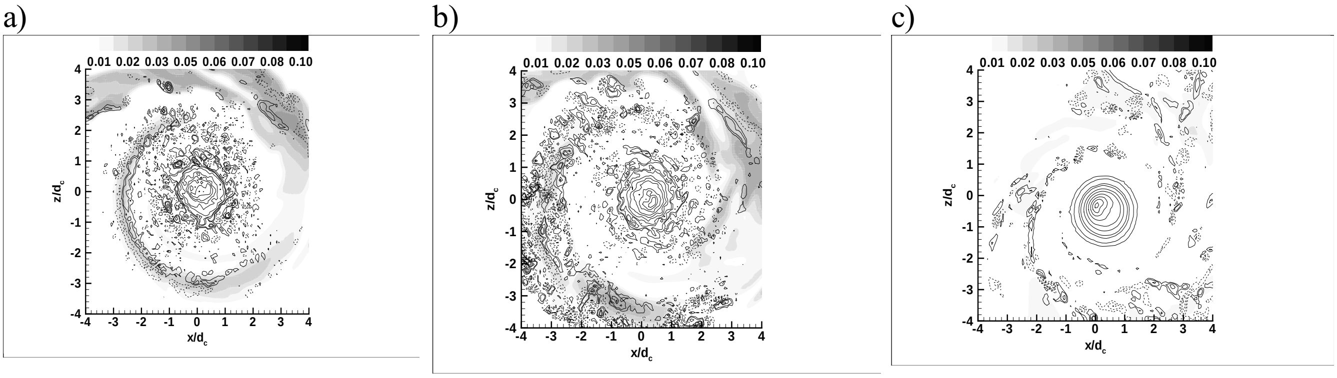

Figure 2. Numerical axial component of vorticity ω_y in a meridional cross plane. Contour range from –1 to 4 in steps of 0.2 for levels between –1 and 1, and in steps of 0.5 for levels between 1 and 4. Exhaust gas concentration is represented by gray flood contours. (a) *y/b*=6.5, (b) *y/*b=9.2, (c) *y/b*=13.1.

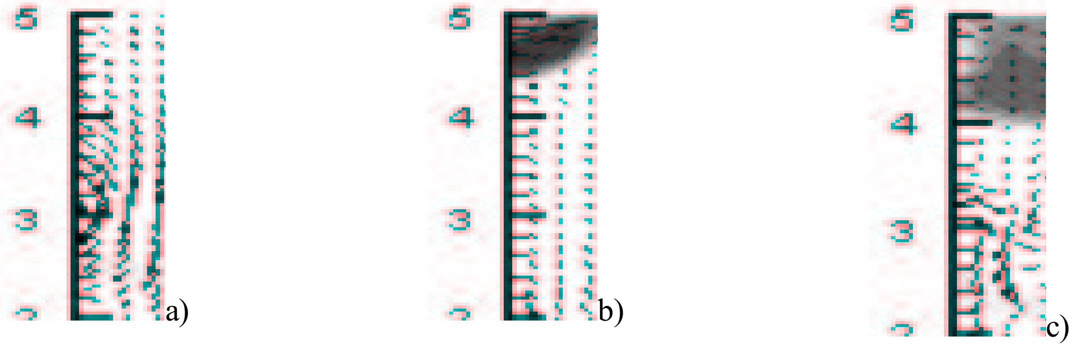

Figure 3. Velocity vector fields in (y,z) plane, at x = 0. Exhaust gas concentration is represented by gray flood contours. (a) *y/b*=6.5, (b) *y/*b=9.2, (c) *y/b*=13.1.

It is also noticed in Figure 3 where velocity vectors are superimposed on the species distribution. Entrainment process results in the trapping of the gas exhaust into the large scale secondary vortices (see Figures 3a and 3b). The species concentration provides a reliable signature of where the helical instability occurs outside the vortex core. Finally, the resulting species field distribution shows no aircraft exhaust products inside the primary vortex core as observed in Figures 2c and 3c.

3 CONTRAIL FORMATION

This paragraph describes the results of the simulation of ice formation in the near field of an aircraft.

A simple micro-physics model for ice growth has been used to couple ice and vapor phases. LES have been carried out at a realistic flight Reynolds number to evaluate the effects of turbulent mixing and wake vortex dynamics on ice growth characteristics and vapor thermodynamic properties.

In the first simulation, the micro-physics ice growth model is switched off. The aim is to obtain a reference mixing case at high Reynolds numbers typical of aircraft wake configurations. It was also useful to analyse the spatial distribution of supersaturated particles and identify the regions where ice formation is most likely to occur.

All particles are initially (at t = 0.16 s) placed below the saturation curve $p_s(T)$ because they are still concentrated inside the hot jet region. Due to the mixing with cold air, particles cool, until some of them become supersaturated (crossing of p_s curve at t = 0.56 s). The spatial distribution of supersaturated particles is given in Figure 4, together with a plane cut of water vapor content at two times during the jet phase. The figure shows that air first saturates around the particles, placed at the edges of the jet where the temperature is fallen and there is sufficient vapor to condense.

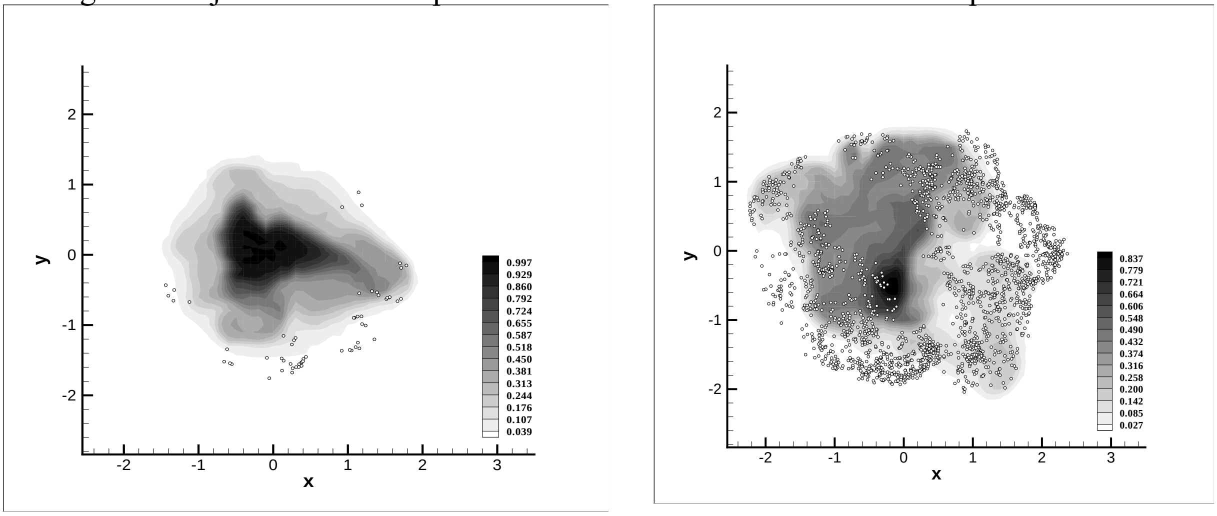

Figure 4. Passive particle case (jet phase). Plane cut of vapor content and distribution of supersaturated particles ; left, t = 0.56 s ; right, t = 0.7 s.

a)

b)

c)

d)

Figure 5. Passive particle distribution during the jet/vortex interaction phase. Dry soot particles are represented in black, iced supersaturated particles in white. Total vorticity iso-surface identifies the vortex core and the secondary vortical structures due to the interaction with the jet ; a) t = 0.7s ; b) t = 1s ; c) t = 1.5 s ; d) t = 2 s

The dynamics of the interaction phase are dominated by formation of three-dimensional structures of azimuthal vorticity associated to the entrainment of the jet inside the vortex field. These structures progressively decay (t = 2 s, see Figure 5(d)), corresponding to complete entrainment of the exhaust jet. This mechanism of entrainment enhances mixing with external air : therefore, exhaust cooling and vapor condensation are favored by the presence of vortex. Figure 5 shows that at t = 2 s all particles are supersaturated and contrail can form everywhere in the wake.

Figure 6. Trajectories of three sample particles in a T - p_w plane.

Figure 7. Time evolution of three sample particles radius.

In the second simulations set, the ice growth model is activated. The aim of this calculation is to analyse the early-stage evolution of the contrail and how it influences mixing and the thermodynamic properties of the vapor. Figure 6 displays the trajectories of three sample ice interaction phase when ice/vapor-pressure plane (results are reported only during the interaction phase when ice/vapor coupling is significative). The figure shows that condensation causes large deviations from the mixing line because of vapor removal and the consequent decrease in water partial pressure p_w. In addition, all the particles finally collapse on the saturation curve, $p_s(T)$, which indicates the thermodynamic equilibrium between vapor and ice phases. This is confirmed in Figure 7 by the evolution of ice-particle radii which attain plateau values between 3 and 6 µm.

4 CONCLUSION

This work is focused on the simulation of contrails and early stage evolution in the near-field of an aircraft wake. A numerical simulation of the interaction between an engine jet and a wake vortex has been performed.

To illustrate the entrainment and mixing processes of the exhaust gas, the examination of axial vorticity contours showed that the turbulence induced by the exhaust jet is wrapped around the wing-tip vortex. Results show that the dynamics of the interaction phase are dominated by formation of three-dimensional coherent structures associated to the entrainment of the jet inside the vortex field The evolution of this interaction (i.e. generation of small scale motions close to the vortex core and rearrangement to coherent secondary structures) mainly controls the gaseous exhaust dispersion.

To study the formation of contrail, a simple micro-physics model for ice growth has been used to couple ice and vapor phases. LES have been carried out at a realistic flight Reynolds number to evaluate the effects of turbulent mixing and wake vortex dynamics on ice growth characteristics and vapor thermodynamic properties.

Two simulation sets are made :

- The first simulation is carried out when the micro-physics model is switched off in order to obtain a reference mixing case at high Reynolds numbers, typical of aircraft wake configurations. This analysis provided the spatial distribution of supersaturated particles and it identified the regions where ice formation is most likely to occur. Furthermore, results show that the exhaust cooling and vapor condensation are favored by the presence of vortex.
- The second numerical simulation is performed accounted for ice growth process in order to analyse the early-stage evolution of the contrail and its influence on the mixing and the thermodynamic properties of the vapor. Results show that condensation causes large deviations from the mixing line because of vapor removal and the consequent decrease in water partial pressure. In addition, all the particles finally collapse on the saturation curve and their radii reach plateau values between 3 and 6 µm.

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