Numerical Simulation of Exhaust Dispersion and Contrail Formation in the Near-Field of an Aircraft Wake

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Collaborations

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Motivation and Objectives

- Contrails are ice clouds formed by condensation of water vapour on nucleation sites, like soot or aerosols, emitted by aircraft engines.

- They artificially increase cloudiness and trigger the formation of cirrus clouds, thus altering climate on local and regional/global scales.

- Nature article (2002): anomalous increase in DTR (daily temperature range) reported over US during the no-flight days of 11-14 Sept. 2001, which is thought to be due to absence of contrails.

Contrail formation close to airports

Contrails visible as thin streaks (South-Eastern France)
Exhaust dispersion in the near-field of an aircraft wake

Interaction engine jets and aircraft wake vortices

Formation and growth of ice particles and aerosols
Phenomenology of wake dynamics

\( Y/b < 0-1 \): Engine jets mix with air, vorticity rolls up into a pair of trailing vortices

\( Y/b < 1-20 \): Jets partly wrap into vortices and partly detrain into buoyant plume

\( Y/b > 20 \): High atm. turbulence level \( \rightarrow \) turbulence dominates dynamics

\( \) Low atm. turbulence level \( \rightarrow \) buoyancy & turbulence \( \rightarrow \) vortex instability
Turbulent mixing engine jet / wake vortex

- Two overlapping regions
- Co-flowing jet (~ $D_j$)
- Entrainment and shearing processes (~ span)

Jet region ~ 50 nozzle exit diameters

Entrainment region 1-15 wingspan
Method of investigation

3D Numerical simulation DNS/LES

Part. I: Aircraft wake dynamics (DNS)
- 1st step: Turbulent jet development (1.2 million points)
- 2nd step: Accounting for the jet/wake interaction (6.5 million points)

Part. II: Particle formation in the near-field of an aircraft wake (LES)
- Contrail & Aerosol formation

Experimental database
- NEARFIELD BEHAVIOR?
- Realistic similarity: Large transport aircraft

Reference quantities:
- jet nozzle radius $R_j = 5 \times 10^{-3}$ m
- $U_j = 60$ m/s
- $U_0 = 20$ m/s
Numerical tool

- **3D Unsteady Compressible Navier-Stokes**
  - Spatial discretization: 6th order compact scheme of Padé
  - Time integration: Runge-Kutta 3rd order
  - Tracer Concentration Equation (Passive scalar: Any pollutant)

- **Direct Numerical Simulations / Large Eddy Simulations**
  - Sub-grid scale models (Hybrid Smagorinsky, FSF)
    - SGS heat flux model

- **Particle Transport and Growth**
  - Lagrangian particle tracking
  - Ice growth model: Fukata & Walter model
    - Vapor / ice mass coupling
  - Aerosol model
    - « multi bin » approach
Experimental setup

NACA - 12 Wing Model
- Wingspan : 50 cm
- Angle of attack: 9°

Hot jet Devices
- Jet diameter : 1 cm
- Maximum temperature : 600 K

Wind Tunnel Facilities
- 1.80 m x 1.40 m x 5 m
- LDV :
  3D mean & fluctuating velocity
- Thermocouple: mean temperature
- Hot wire

Part I. DNS Plume dynamics
Flow configuration: Jet flow behavior

**Initial velocity profile**

\[
U(r) = \frac{1}{2} (U_j + U_0) - \frac{1}{2} (U_j - U_0) \tanh \left( \frac{1}{4} \frac{R}{\theta} \left( \frac{r}{R} - 1 \right) \right)
\]

- **Radius** \( R \) \( \rightarrow U(R) = \frac{1}{2} (U_j - U_0) \)
- **\( \theta \) Momentum boundary layer thickness**
  \[
  \frac{R}{\theta} = 10 \quad \rightarrow \quad \text{Michalke and Hermann (1982)}
  \]

**Reynolds number**

\[
Re = \frac{U_j R}{\nu} = 1000
\]

**Estimation of the end of the “jet region”**

Numerical profile fits to experiment
Flow configuration: turbulent jet / vortex interaction

- Initial Trailing vortex: 2D Lamb-Oseen Vortex
- The circulation based Reynolds number: \( Re = \frac{\Gamma c}{v} = 5000 \)
- Turbulent jet located at \( 7d_c \) with respect to the vortex center
- Computation performed in a larger grid: \( 327 \times 327 \times 61 \)

\( d_c \) reference quantity: vortex core diameter

Experiment vs DNS: \( Y/b = 0.5 \)
Part I. DNS Plume dynamics

Engine jet / Wing-tip vortex interaction
radius profile of circulation

\[ \Gamma \]
\[ r \]
Engine jet / Wing-tip vortex interaction

Part I. DNS Plume dynamics

Turbulent engine jet → Kelvin-Helmotz instability
Part I. DNS Plume dynamics

Experiment/Numerical simulation: Comparison

Normalised temperature contours in a vertical lateral cross-section

[Images showing temperature contours with labels: Experiment and Numerical simulation]
Part I. DNS Plume dynamics

**Experiment/Numerical simulation: Comparison**

- **Tangential Velocity profiles and temperature evolution in the wake vortex**
- **Numerical predictions are in agreement with the experimental results**
Flow dynamics: Turbulent jet entrainment

**Part I. DNS Plume dynamics**

**Step I**
- Entrainment and deflection of the jet
- Fully turbulent state

**Step II**
- Interaction jet/wake vortex
- Development of secondary vorticity structures (SVS)

**Step III**
- Connection of SVS: Linking process
- Stabilizing effect of flow rotation
Flow dynamics: Turbulent kinetic energy

- Increase of energy likely due to the development of the large-scale vortical structures (SVS)
How does the wake dynamics affect the scalar mixing?

Axial vorticity and scalar concentration

Outside the wing-tip vortex
Scalar mixing: Velocity vectors and Passive scalar

Part I. DNS Plume dynamics

- Concentration of the passive scalar
- Breakup process
  - Spreading of the scalar field
  - Redistribution in small-scale eddies
- Vortex core
- Helical structures
Scalar mixing: Scalar fluxes

Part I. DNS Plume dynamics

Close to the vortex center
- Radial and (tangential) components negligible contribution
- Importance of axial component $\langle Z'U'_y \rangle$
Particle formation in the near-field of an aircraft wake
Soot particles

They form mainly in the fuel-rich primary zone of the combustor (before the flame front) because of incomplete combustion.

Emission index 0.01-0.04 g/kg of fuel burnt, \(3-10 \times 10^{14}\) particles/kg (modern), 0.1 g/kg and \(3 \times 10^{15}\) particles/kg (old)

Average 0.04 g/kg

Mean diameters 20-60 nm

Soot concentration at the nozzle exit \(\approx 10^7\) cm\(^{-3}\)
Size distribution of soot particles-RB211
Rolls-Royce Company
"Chemi-ions"

Ions are produced in the combustor in very high quantities in the flame front. Chemi-ionisation rate up to $10^{17}$ cm$^{-3}$s$^{-1}$

Ion emission index $E_{I_i}$, about $1-5 \times 10^{16}$ ions/kg fuel.

Concentration at the nozzle exit of about $10^8$/cm$^3$
Aerosols or « volatile » particles

Always found in an exhaust wake

Formed mostly by binary nucleation of water-sulfuric acid gaseous mixture but include also (probably) hydrocarbons,

Ions participate also to their formation and growth

Their number and size depends on FSC, the fuel sulfur content (for medium and high FSC) and on the sulfur conversion factor [S(IV) to S(VI)]

Emission index : 2-5x10^{17}/kg

Size : diameter 2 – 20 nm

Difficult to measure (no size distribution available)
Part II. Particle formation in the wake

**Contrail and Aerosol formation**

- **Homogeneous Nucleation**
- **Heterogeneous nucleation**
- **Coagulation**
  - $S_w < 1$
  - $S_w > 1$
- **Condensation and freezing**
- **Freezing**
- **Binary Nucleation** (ionic and neutral)
- **Condensation**
- **Coagulation**

**Chemical Processes**

- $H_2SO_4(g)$

**Processes Diagram**

François GARNIER – PRF 2005
Part II. Particle formation in the wake

Contrail & Aerosol Modelling

- Precursors initialization
  - Neutral hydrates distribution
  - Chemi-ion (single charge)

- Gas phase species: $\text{H}_2\text{O}$, $\text{H}_2\text{SO}_4$

- Particles
  - Soot (size distribution)
  - Activation and growth
  - Soot particles (mixed and dry)

- Collisions
  - Neutral volatile particles
  - Charged volatile particles

Particles
Part II. Particle formation in the wake

Ice particle formation

- Mixing between hot jet and cold air is represented by a straight line in a T-pw plane.

- Ice crystals form if vapour becomes supersaturated with respect to water (ice), pw > psat AND a nucleation site (typically soot particle) is present.

Particle simulation conditions

- LES approach: Re = 3.2 \times 10^6
- T_\text{ambient} = 225k, T_j/T_a = 2
- Y_{water} = 0.03
- Particle number density: 2.5 \times 10^{11}
  Numerical particles: 2.5 \times 10^5
  Particle radius: 0.02 \mu m
Ice particle modelling

- Vapour/ice phase exchange → Vapour condensation on the soot particles

\[
\bar{\omega}(x) = \frac{\bar{r}^3}{Y_{v0}} \cdot \frac{1}{V(x)} n_{\text{trans}} \sum_{k=1}^{n_p} \rho_p 4\pi r_p^2 \frac{dr_p}{dt}
\]

Saturation ratio

\[
r_p \frac{dr_p}{dt} = \frac{L^2 M_w \rho_p}{k_g RT_g f_{3a}} A + \frac{\rho_p RT_g}{P_{\text{sat}} D_v M_w f_{3b}}
\]

Kelvin effect: Particle curved interface

Kinetic factors: Growing surface / Evaporating water droplets

Part II. Particle formation in the wake
Engine jet: Where does ice appear?

Vapor content (red = high) and supersaturated particles (white)

Note: particles start to form at the edges of the jet
Engine jet: Where does ice appear?

Vapour content in \((y,z)\) plane cut and distribution of particles

Black: Dry soot particles
White: Supersaturated particles
During mixing and cooling particles become supersaturated.

Part II. Particle formation in the wake

Joint PDF of T and $p_w$ around particles

Y = 15 m
Y = 20 m
Y = 25 m
Y = 50 m
How does vortex affect condensation?

- Engine jet is entrained by the vortex field
- Vortex increases mixing of the jet with cold air (favours ice formation)
How does condensation modify mixing?

Part II. Particle formation in the wake
How does condensation modify mixing?

Crystals grow until local ice/vapour equilibrium is achieved.

Vapor removal causes large deviations from the mixing line.
Part II. Particle formation in the wake

aerosol and ice particle size spectra in the vortex wake for $t = 3$ s

- Number- size distributions are in good agreement with in-situ experiment « AEROCONTRAIL »
- Bimodal distribution of size spectra for aerosols
Influence of ions in the vortex wake for t = 2.5 s

Part II. Particle formation in the wake
Part II. Particle formation in the wake

**New generation of aircraft engines with higher propulsion efficiencies**

→ Cause more contrails (Schumann et al., 2000)

Airbus A-340

Boeing 707
Conclusions (I)

- Compressible DNS and LES of the aircraft wake
  - Engine jet region
  - Jet merging in a trailing vortex

- The Engine jet wraps around the vortex
  - Development of counter-rotating secondary vortices (SVS)
  - Exhaust high dispersion (favoured by large-scale vortex)

- Accurately predict the thermodynamic conditions in the near-field of an aircraft wake
  - Contrail formation
    - Soot and ice particles (Lagrangian viewpoint)
Conclusions (II)

- Influence of aircraft wake dynamics and turbulent mixing
  - Vapor first supersaturates at the edges of the engine jet
  - Accounting for vapor depletion results in significant deviation from the classical mixing line
    - Responsible for polydispersion of particle radii
  - Bimodal distribution of size spectra for aerosols
- Aerosols & contrails ➔ Number-size distributions
  - In good agreement with in-situ experimental data