Compressible effects on ice particle growth in turbulent jets

E. Maglaras*, F. Garnier

Office National d'Etudes et de Recherche Aérospatiales, 29, av. De la Division Leclerc, BP 72, 92322 Châtillon, France

Abstract

In order to understand the process of formation of condensation trail (contrail), the flow in the near field of an engine jet is numerically studied. Three-dimensional temporal evolution of a non-isothermal turbulent round jet laden with solid particles is modelled using the large eddy simulation technique. The particles are tracked by the Lagrangian approach and their growth is calculated by a microphysics model of vapour condensation and ice formation. We only consider water mass exchange between the two phases of the fluid. A series of simulations has been performed with a low Mach number ($M = 0.2$) and a moderate one ($M = 1$) at a realistic Reynolds number ($Re = 3.2 \times 10^6$). To determine the compressibility effects on the evolution of particles, we examine their spatial distribution and their growth at the different Mach numbers.

Keywords: Large eddy simulation; Temporal simulation; Compact schemes; Turbulent heated jet; Compressible effects; Growing ice particles; Lagrangian approach

1. Introduction

The formation of ice particles in the aircraft jet is a subject of growing interest since they may have an impact on cloudiness and may affect the Earth's radiative budget balance. Aircraft exhaust contains products resulting from combustion in gas or solid phase [1]. For favourable ambient relative humidity and temperature, these emissions can lead to ice particles formation, i.e. contrails. In the last years, several studies have been performed in order to examine the theoretical understanding of the mechanisms responsible for the formation of these particles. In addition to the formation process itself, further attention has been given to other important processes such as turbulent mixing phenomena in the engine exhaust. The study is focused on the 3D simulation of contrail formation. In this work, we will more specially examine compressibility effects on the particle evolution throughout the heated turbulent jet. This represents a complex issue involving different multi-scale phenomena such as jet instabilities, compressible turbulent mixing, two-phase flow and microphysics.

2. Model problem and results

2.1. Equations and numerical modelling

The numerical simulations of the flow are based on the use of 3D temporal large eddy simulation (LES) of the compressible Navier–Stokes equations together with a transport equation for a scalar field representing the exhaust water vapour. In the LES approach, these equations are filtered in order to reduce the number of scales to be solved. Among the SGS viscosity and SGS heat flux models tested in a recent work of Ferreira Gago et al. [2], the compressible version of the hybrid Smagorinsky model (linear combination of the Smagorinsky and the similarity model) displayed the best performances, especially when dealing with the turbulent stresses and turbulent heat flux. The LES equations are solved by using a sixth order compact scheme in space and the time marching scheme is a third-order Runge-Kutta algorithm. We add a MSOU Superbee limiter for the scalar equation, which contains a source term to take into account the ice/vapour mass coupling. As for modelling particles, we use the alternative Lagragian particle tracking approach: each particle is followed individually in the carrier gas. Due to the small size of soot–ice particles (from tens of nanometres to a few microns), their relaxation time is negligible

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* Corresponding author. Tel.: +33 (1) 46 73 47 97; Fax: +33 (1) 46 73 41 48; E-mail: Ephi.Maglaras@onera.fr

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compared to the characteristic times of the filtered variables. This allows them to be treated as a tracer. Furthermore, because of the high number density of particles, we can carry on only packets of particles, i.e. one numerical particle contains a large number (10^6) of physical particles. Its position is calculated by solving Eq. (1) with the sixth-order Adams-Bashforth method:

$$\frac{\partial x}{\partial t} = v \tag{1}$$

The ice-growth process is performed using the Fukuta-Walter model [3] given by Eq. (2), which is solved with a fourth-order Runge-Kutta algorithm:

$$r_p \frac{dr_p}{dt} = \frac{S - A}{C} \tag{2}$$

This model calculates the particle radius r_p considering the Kelvin effect (A), the saturation ration (S), and the thermodynamic properties of the different phases of water through the term C. From this resolution we deduce the rate of growth which is used for expressing the coupling term in the LES equations.

2.2. Initial jet flow configuration

The domain is illustrated in Fig. 1, where $r_j = 0.5\,\text{m}$ is the jet radius and the uniform space step is $\Delta x = 0.1 r_j$. Periodic boundary conditions are used along the jet axis and non-reflecting boundary conditions [4] on the X–Z directions. In this study, we compute a realistic Reynolds number, $Re = 3.2 \times 10^6$, and two Mach numbers are tested: low compressibility ($M = 0.2$) and moderate compressibility ($M = 1$), which is more representative of the jet engine flow. The jet core temperature is $T_j = 440\,\text{K}$, the external one is $T_a = 220\,\text{K}$, and the exhaust vapour molar fraction is equal to $X_{vj} = 0.03$, which is a typical value at the exit nozzle [5]. Axial velocity, temperature and vapour molar fraction are initialized similarly according to a *tanh* law, described by Eq. (3):

$$T(r) = \frac{1}{2}\left(T_j + T_a\right) - \frac{1}{2}\left(T_j - T_a\right) \tanh\left[\frac{1}{4}\frac{r_j}{\theta}\left(\frac{r}{r_j} - \frac{r_j}{r}\right)\right] \tag{3}$$

where r is the radial distance from the jet centre and θ denotes the momentum boundary layer thickness of the jet shear layer. We restrict the present investigation to one value of the jet parameter, namely $r_j / \theta = 10$, which corresponds to the most unstable jet velocity profile. Random Gaussian shape perturbations are imposed on the three components of the velocity field. According to Kärcher [6], we randomly place in the jet 10^{10} soot particles/m^3: they are spherical with initial radii $r_0 = 20\,\text{nm}$.

2.3. Sample results

In this section we present a sample of the results obtained by a series of compressible LES simulations to evaluate the effects of compressible turbulent mixing on particle ice-growth characteristics. On comparing in Fig. 2 the temporal evolution of the mean radius of the

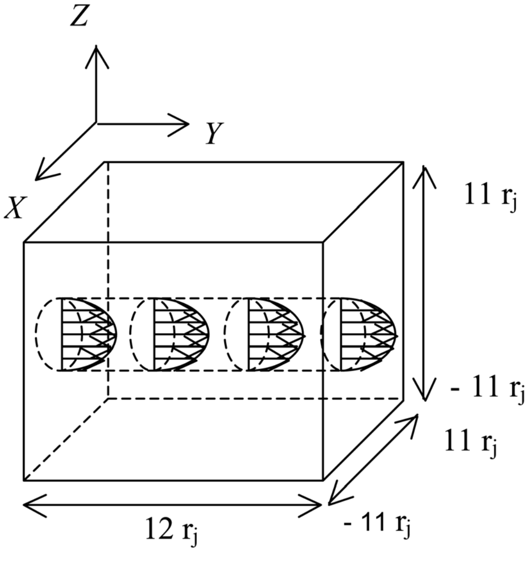

Fig. 1. Domain of resolution.

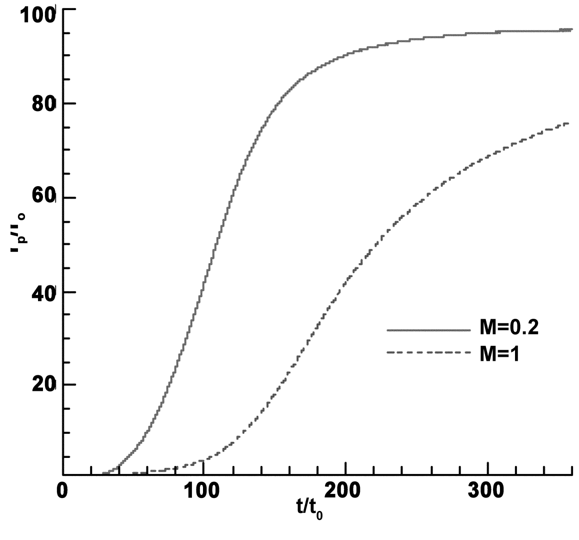

Fig. 2. Temporal evolution of the mean radius of ice particles.

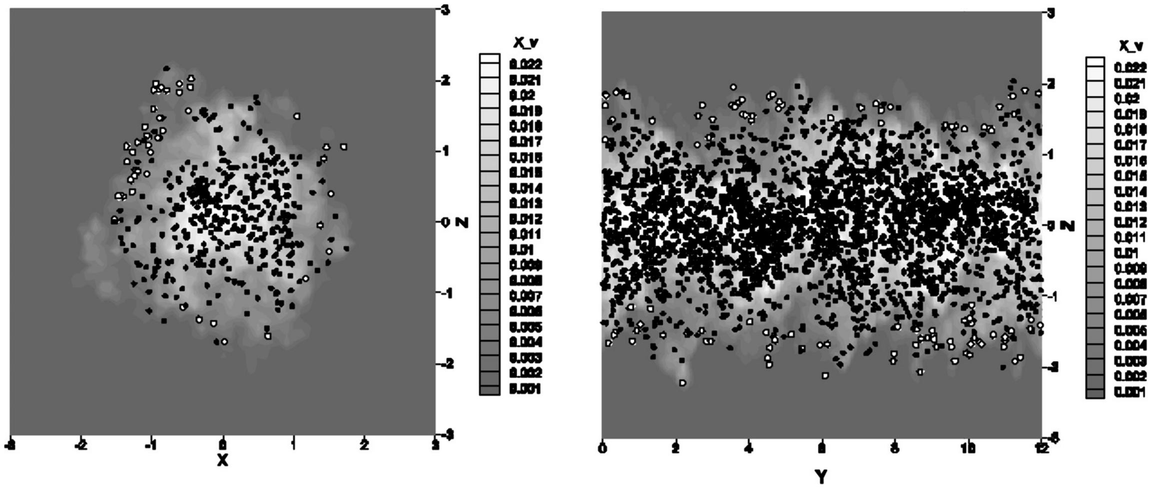

Fig. 3. Vapour content and distribution of supersaturated (white) and dry (black) particles in XZ (a) and YZ (b) plane cut at dimensionless time $t/t_0 = 30$ for $M = 1$.

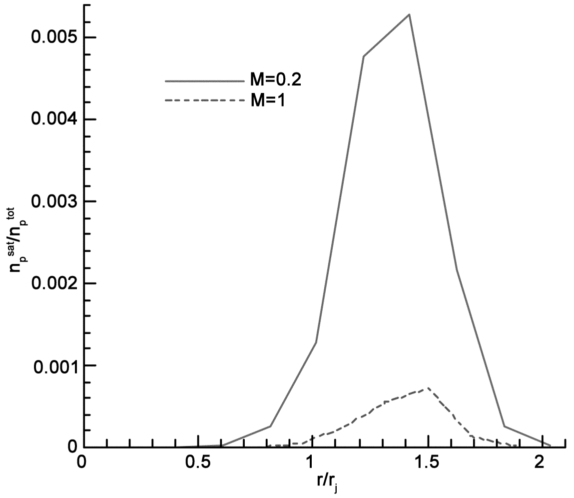

Fig. 4. Radial distribution of supersaturated particles at dimensionless time $t/t_0 = 30$.

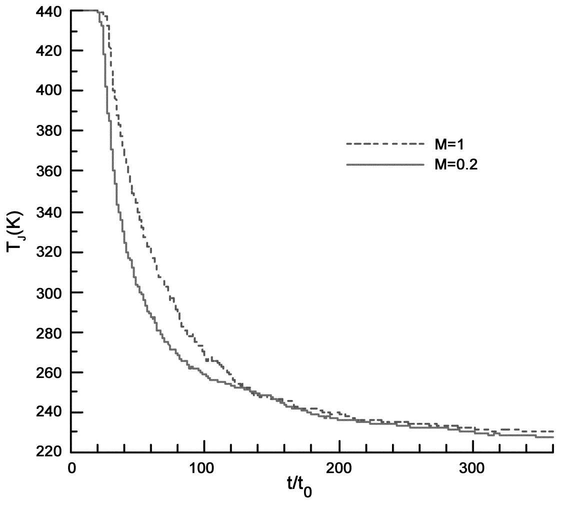

Fig. 5. Temporal evolution of the temperature at the centre of the jet.

particles for different Mach numbers, we can notice that condensation occurs earlier and faster at low Mach number. At dimensionless time $t/t_0 = 360$, the mean radius is equal to 1.9 μm for $M = 0.2$ and has reached 1.5 μm at $M = 1$. Moreover, Fig. 3, where we displayed two different plane cuts of the domain at dimensionless time $t/t_0 = 43$ for $M = 1$, shows that air first saturates around the particles placed at the edges of the jet. At this place the temperature is low and there is sufficient vapour to condense. Figure 4, which displays the radial distribution of supersaturated particles at dimensionless time $t/t_0 = 30$, confirms all these first results: there are more saturated particles for a low Mach number at the shear layer of the jet. This is due to the decrease of temperature and vapour volume fraction which is more rapid at low Mach number. The transition process to turbulence is anticipated when comparing to the case at $M = 1$. Indeed, the growth of perturbations is effectively delayed by compressibility effects and as a consequence hinders the transition to turbulence. This is confirmed as shown in Fig. 5, where we have plotted the temporal evolution of temperature for the two Mach numbers: during the transition process, the temperature drops rapidly. At $M = 0.2$ this decrease is anticipated by the earlier growth of instabilities inside the jet flow when comparing to case $M = 1$.

3. Conclusion

Whatever the considered Mach number, the process of condensation starts at the edges of the turbulent jet, where the hot jet flow is mixing with cold air. Moreover, the first results obtained in this study show that compressibility effects have a strong influence on the formation of contrails; the ice particles form earlier and grow faster at low Mach numbers. This is due to the anticipation of the transition to turbulence which starts earlier the decrease of temperature and vapour molar fraction.

The discussion about the compressibility effects will be deepened in further results presented as a function of physical parameters: the jet flow temperature and the initial distribution of particle radii.

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