IMPERIAL

Ice growth in CPMOD

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PAL configuration

Fagan, A. F., Guzman, F. J., Podboy, D. P., Rabinowitz, M. J., Brusk, K. D., Podboy, D. M., Caldwell, S. J. (2024). Contrails Measurement and Testing Capabilities in NASA's Particulate Aerosol Laboratory. In *AIAA SCITECH 2024 Forum* (p. 1242).

- 6 fuels
  - Jet-A
  - n-heptane
  - Butanol
  - 3 type of SAF

- ICE characterization based on
  - ICE no. density $[\#/m^3]$
  - ICE mean diameter $[nm]$
  - ICE mass density $[g/m^3]$

- Sensitivity studies
  - Soot number density and size
  - Fuel-to-air ratio ($\Phi = 0.24 - 0.36$)
    - Not investigated for SAF
  - Flight altitude

ICE number density

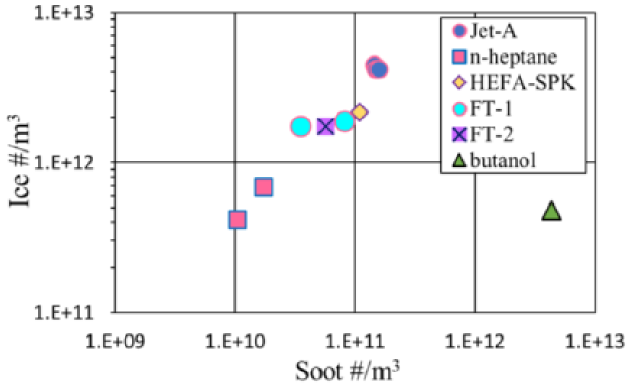


Fig. 16. Ice particle number density versus soot particle number density for various fuels at 40,000 ft and -48°C ambient conditions and a nozzle temperature of 90°C.

ICE mean diameter

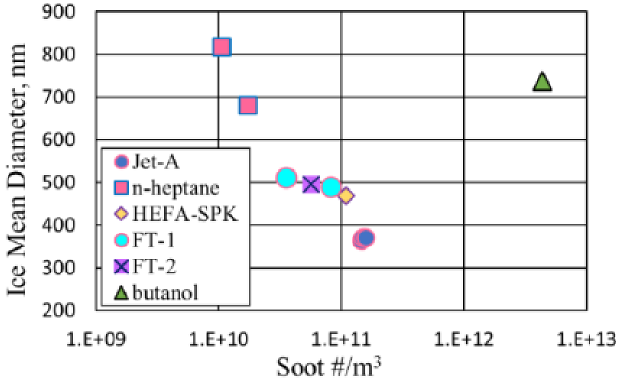


Fig. 17. Ice particle mean diameter versus soot particle number density for various fuels at 40,000 ft and -48°C ambient conditions and a nozzle temperature of 90°C.

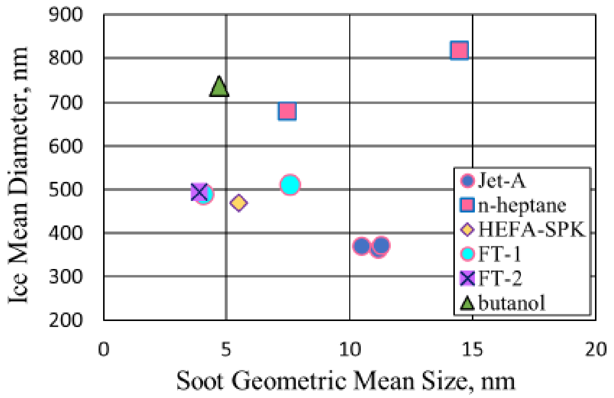
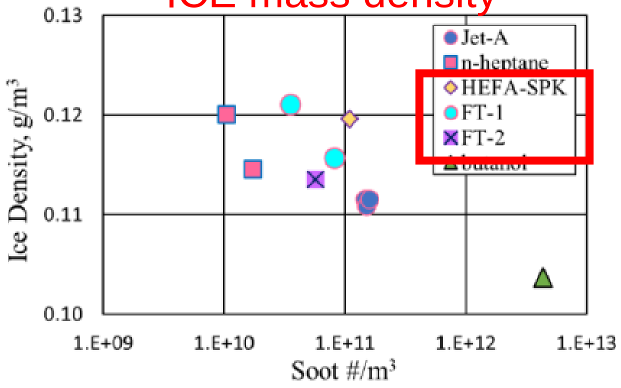


Fig. 18. Ice particle mean diameter versus geometric mean diameter of soot particles for various fuels at 40,000 ft and -48°C ambient conditions and a nozzle temperature of 90°C.

ICE mass density



SAF

Fig. 19. Ice mass density versus soot particle number density for various fuels at 40,000 ft and -48°C ambient conditions and a nozzle temperature of 90°C.

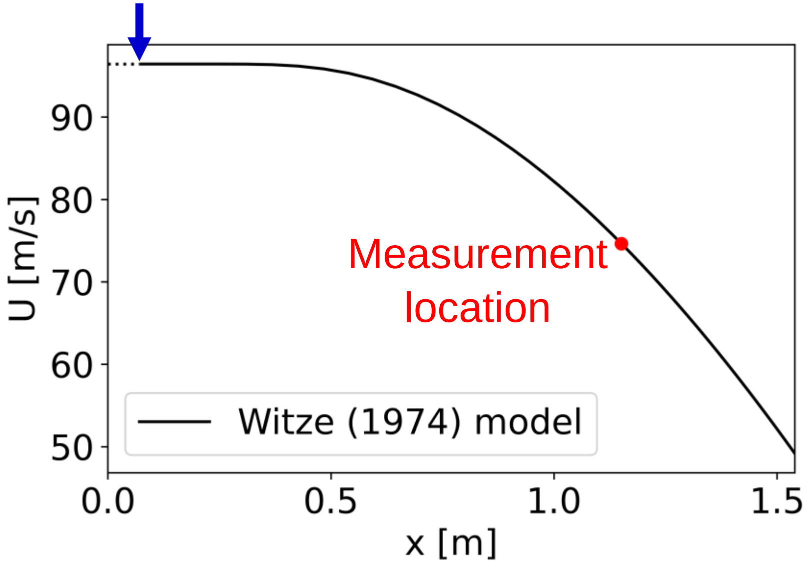
Jet centreline model

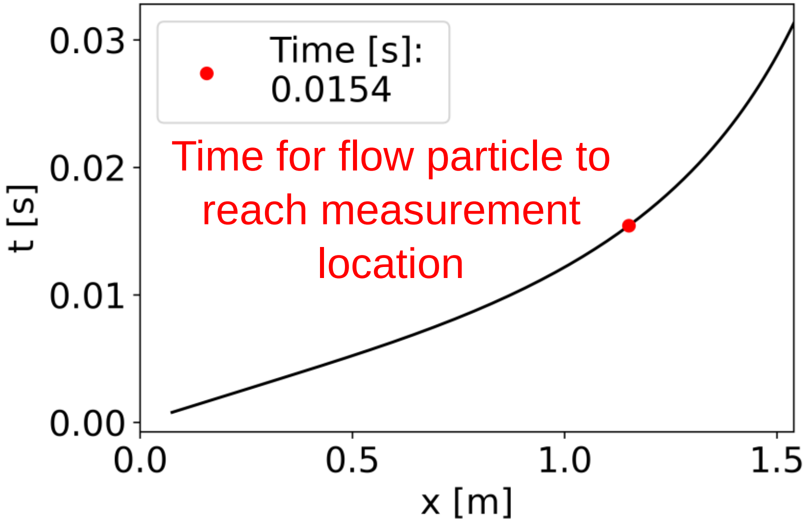
$$V_{j,0} = 96.4\frac{m}{s}$$
$$T_{j,0} = 363.15\ K$$
$$T_a = 225.15\ K$$
$$p_a = p_j = 18753.93\ Pa$$

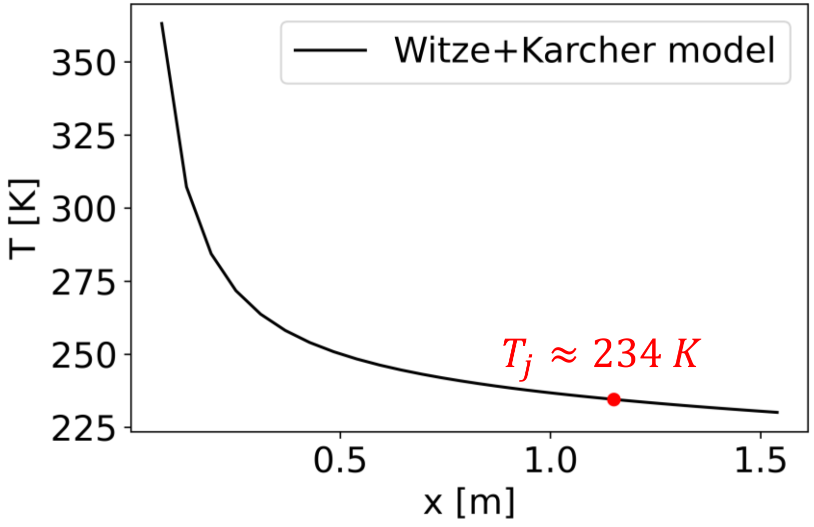
Convective time unit

$$t_c = \frac{L}{V_{j,0}} \approx 0.012s$$

Jet plume
mixing time scale





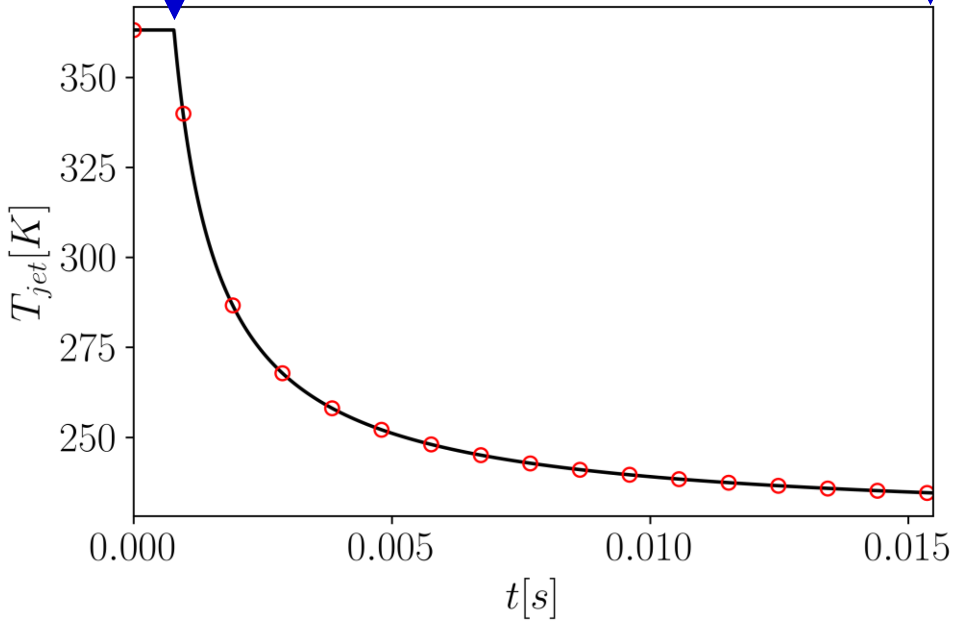


CPMOD studies

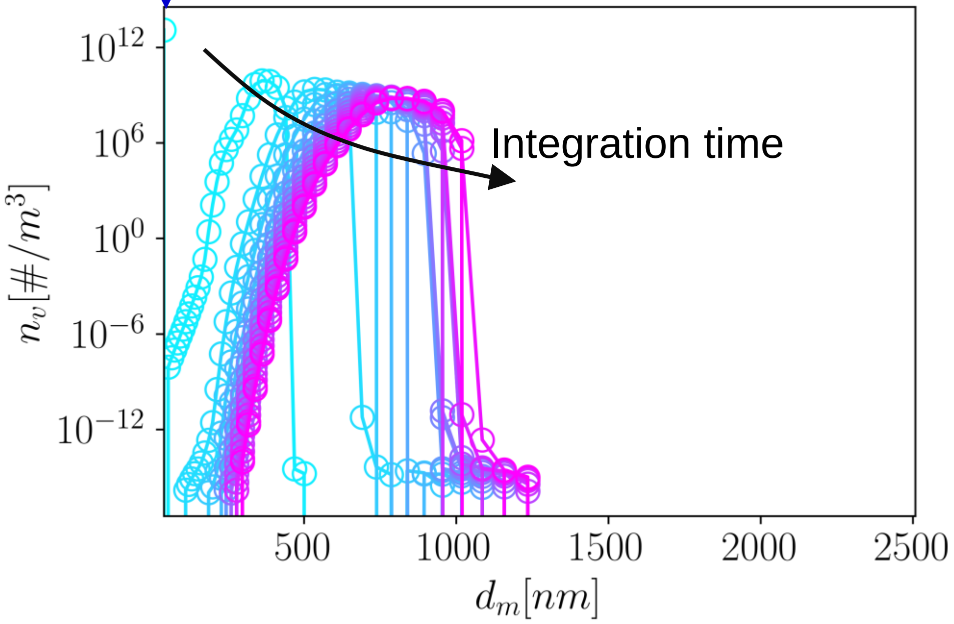
Ice growth in non-stationary homogeneous environment

Jet plume mixing time scale

Final integration time



t=0: monodispersive distribution



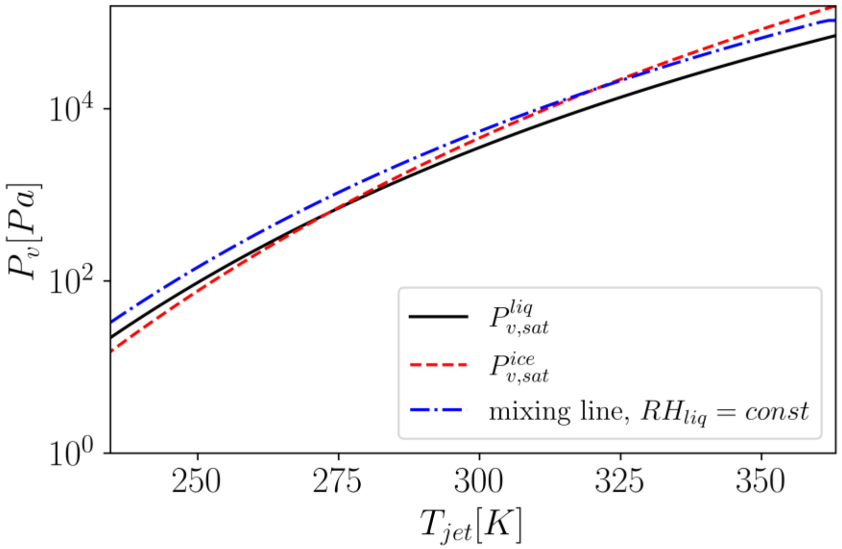
- Temperature follows jet cooling rate model
- Assumptions
  - Relative humidity, RH_{liq}=1.6 (constant – no supersaturation consumption, nor dilution)
  - Soot particle radius, $r_{p,0} = 20\ nm$ (Lewellen, 2020)
  - Soot particle (mass) density, $\rho_{p,0} = 1550\,\frac{kg}{m^3}$ (Karcher et al., 2015)

Ice depositional growth model
Saturation vapor pressures over ice and liquid

$$p_{\text{ice}} = \exp(9.550426 - 5723.265/T + 3.53068\ln(T) - 0.00728332T); \quad T > 110\,\text{K}.$$

$$\begin{aligned}\ln(p_{\text{liq}}) \approx\ & 54.842763 - 6763.22/T - 4.210\ln(T) + 0.000367T \\ & + \tanh\{0.0415(T - 218.8)\}(53.878 - 1331.22/T \\ & - 9.44523\ln(T) + 0.014025T);\end{aligned} \tag{10}$$

for $123 < T < 332$ K.



Murphy, D. M., & Koop, T. (2005). Review of the vapour pressures of ice and supercooled water for atmospheric applications. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, *131*(608), 1539-1565.

Ice depositional growth model

Linear growth rate – Karcher et al 1996

Radial growth rate of ice particle $$\frac{dr_p}{dt} = G(r_p) D_v \frac{p_v - p_{v,sat}^{ice}}{\rho_p r_p}$$

r_p: particle radius
ρ_p: particle density

Where:

$G(r_p) = \frac{1}{\left(\frac{1}{1+Kn} + \frac{4Kn}{3\ \alpha}\right)}$ - collision factor – accounts for transition from gas kinetic to continuum regime

$Kn = \frac{\lambda_{water}}{r_p}$ - Knudsen number

$\lambda_{water} = f(T, p)$ - water vapor mean free path

$D_v = f(T, p)$ - diffusion coefficient of water vapor molecules in air

$\rho_p = \frac{\rho_{p,0} r_{p,0}^3 + \rho_{ice}(r_p^3 - r_{p,0}^3)}{r_p^3}$ - with $\rho_{ice} = 917.0 \frac{kg}{m^3}$ (neglecting soot core, but can be refined based on Khou et al. 2015)

Kärcher, B., Peter, T., Biermann, U. M., & Schumann, U. (1996). The initial composition of jet condensation trails. *Journal of atmospheric sciences*, *53*(21), 3066-3083.
Khou, J. C., Ghedhaifi, W., Vancassel, X., & Garnier, F. (2015). Spatial simulation of contrail formation in near-field of commercial aircraft. *Journal of Aircraft*, *52*(6), 1927-1938.

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r_p: particle radius
ρ_p: particle density

In BOFFIN+CPMOD:
$p_v = pX_{water}$ - with X_{water}: water mole fraction (field variable)

In CPMOD/PSR:
$p_v = p_{v,sat}^{liq}RH$ – with RH: relative humidity (user input)

Kärcher, B., Peter, T., Biermann, U. M., & Schumann, U. (1996). The initial composition of jet condensation trails. *Journal of atmospheric sciences*, *53*(21), 3066-3083.