Highly-resolved simulations of contrail formation generated by fuel cell propelled aircraft

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Overview

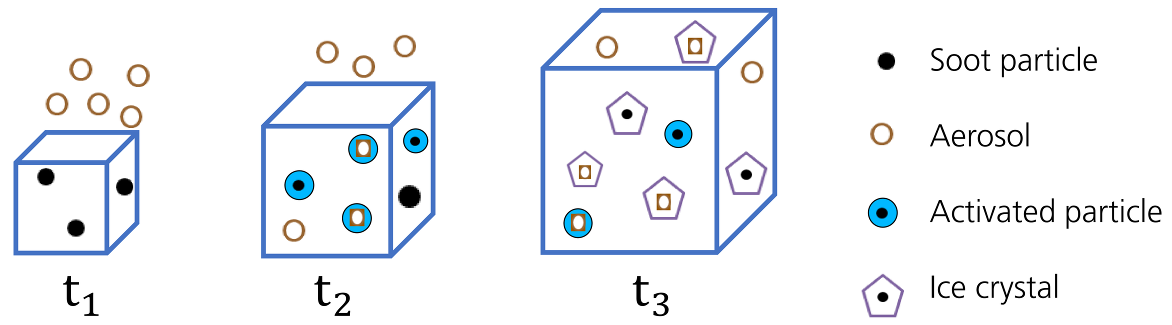
The goal for sustainable aviation requires to develop new propulsion technologies. Fuel cells fueled with hydrogen (H_2) are one promising alternative since no CO_2 is emitted. Moreover, it is also essential to investigate the impact of non-CO_2 effects: NO_x is not emitted anymore but a higher quantity of water is emitted (vs kerosene), which can affect the formation of contrails, their properties and therefore their climate impact. The number of ice crystals formed in the first few seconds of the plume influences the climate impact of a contrail.

Our study generalizes the classical contrail formation theory to capture very moist plumes that might occur behind future aircraft. For fuel cell propulsion we introduce new emission reduction factors to account for possible heat and water vapor management. Highly resolved numerical simulations show that the number of ice crystals varies across orders of magnitude depending on the conditions of the fuel cell exhaust and the ambient atmosphere. For very moist plumes Homogenous Droplet Nucleation can influence the number of ice crystals significantly.

Simulations

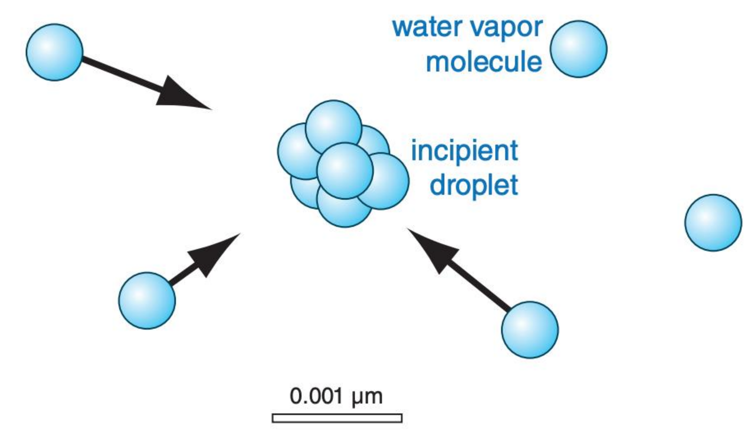
Model

- 0D box model LCM (Lagrangian Cloud Module) with Lagrangian particles, so far used for contrail formation for kerosene and hydrogen combustion
- Mimic dynamical processes via temperature dilution
- Focus on microphysical processes:
  - ✓ Activation of particles into droplets
  - ✓ Condensational/Diffusional growth
  - ✓ Freezing into ice crystals



Homogeneous Droplet Nucleation

- Droplet nucleation without condensation nuclei (HDN)
- Only occurs at very high supersaturation values (RH_w > 500 %)
- Nucleation rate highly non-linear
- Increases the number of ice crystals



Setup

Atmosphere

p_{amb}	{280, 400} hPa
T_{amb}	{210, 230} K
$RH_{i,\,amb}$	100 %
Aerosol	n =1000 cm^{-3}, r = 10 nm

H_2 Fuel Cell

η	{0.3, 0.5}
γ	{1, 0.25}
δ	{1, 0.25}

Contrail formation theory

Classical theory

Assumptions:

- Ambient water vapor and enthalpy can be neglected compared to exhaust conditions
- Specific humidity $\hat{q} = \varepsilon \frac{p_{wv}}{p_{amb}}$
- Constant heat capacity of dry air used

Slope of straight mixing line

$$\frac{\Delta p_{wv}}{\Delta T} = G = \frac{EI_{H20}\, c_p\, p_{amb}}{Q\,(1-\eta)\,\varepsilon}$$

Generalized theory

Revised assumptions:

- Enthalpy $h = \int_{T_{amb}}^{T_{exit}} c_p(q,T)\,dT$
- Specific humidity $q = \frac{\varepsilon\, p_{wv}}{p_{amb}+(\varepsilon-1)p_{wv}}$

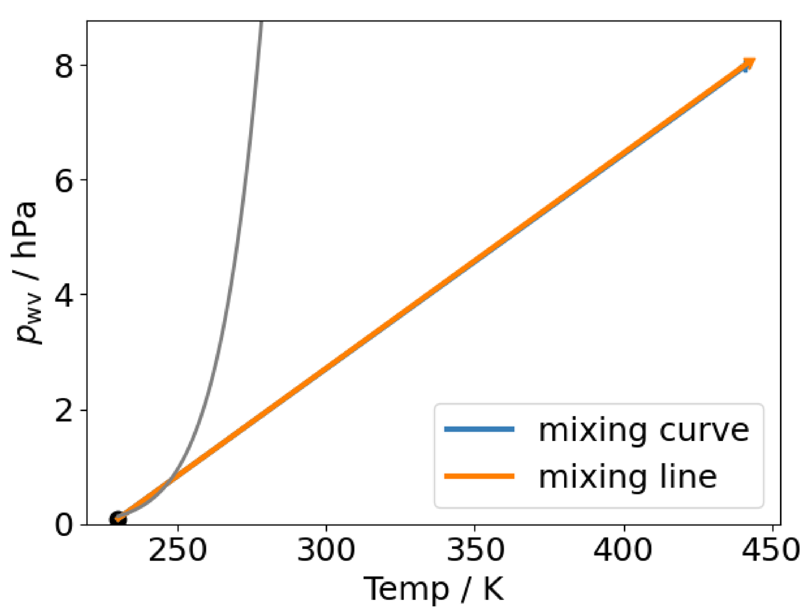
Emission factors

$$\gamma = \frac{\text{emission of water vapor}}{\text{theoretical emission of water vapor}}$$

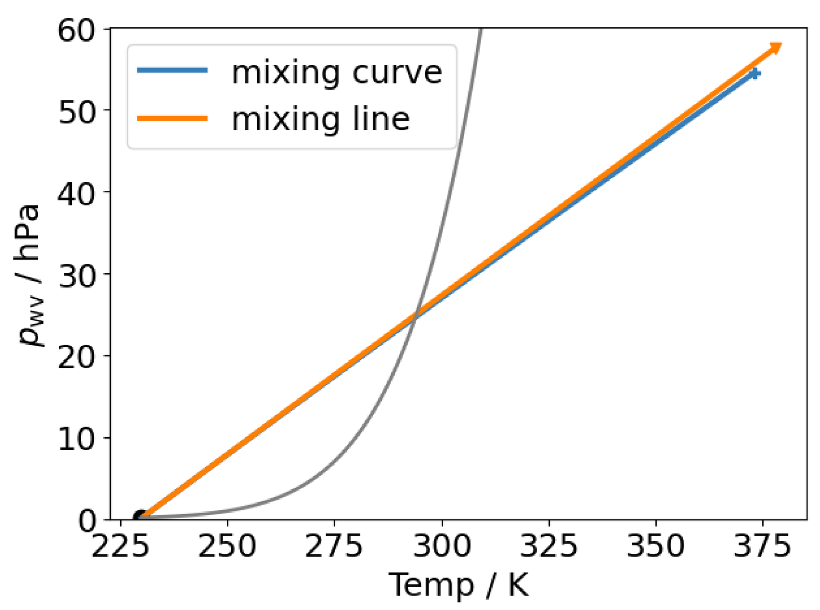
$$\delta = \frac{\text{heat emission}}{\text{theoretical heat emission}}$$

$$G_{FC} = \frac{\gamma\, EI_{H20}\, c_p\, p_{amb}}{\delta\, Q\,(1-\eta)\,\varepsilon}$$

kerosene



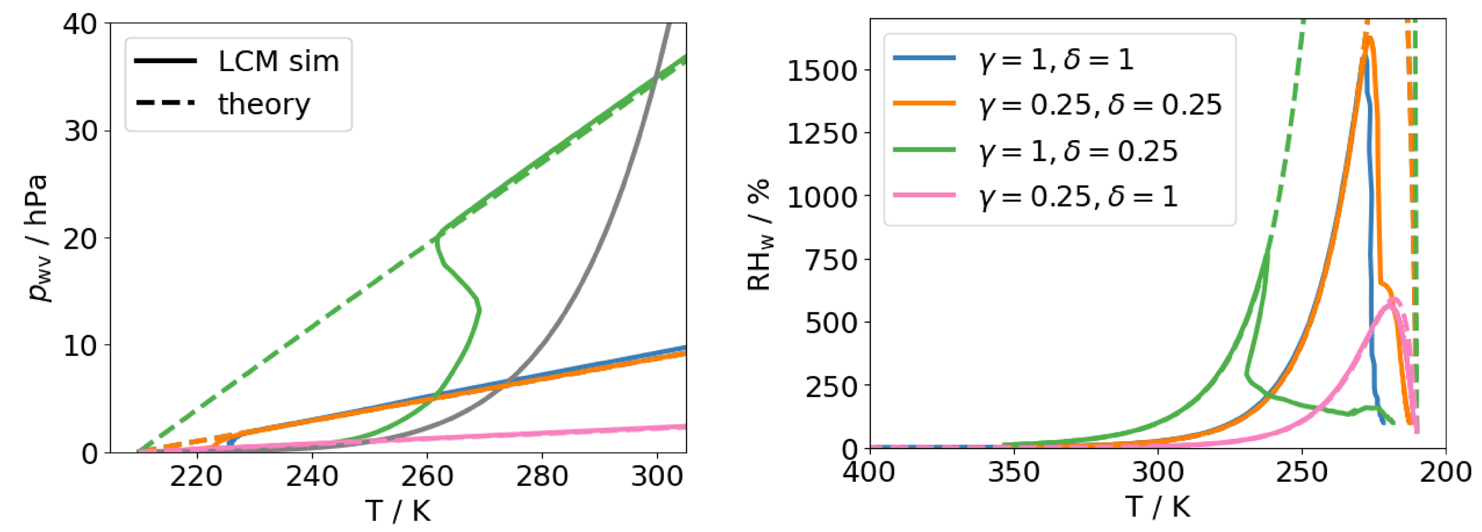
H_2 Fuel Cell, γ=1, δ=0.25



- Effects of approximations of specific humidity and enthalpy cancel each other
- Differences between mixing line and curve are negligible

Results

Thermodynamics



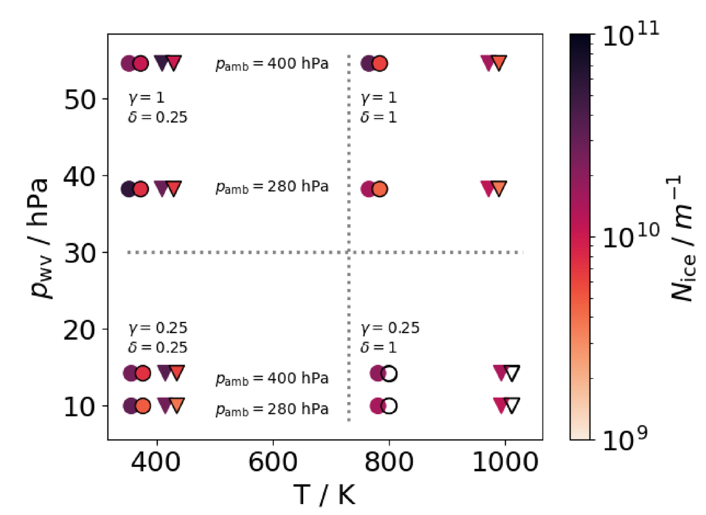
Case: p_{amb} = 400 hPa, T_{amb} = 210 K, η = 0.5

- Evolution of water vapor pressure and relative humidity for different values of γ and δ
- Ambient aerosols and HDN droplets reduce the water vapor in the plume
- Kinks in RH_w indicate HDN formation, which reduces RH_w drastically
- Reduction of water vapor emission leads to lower supersaturation and avoidance of HDN

Ice crystal numbers

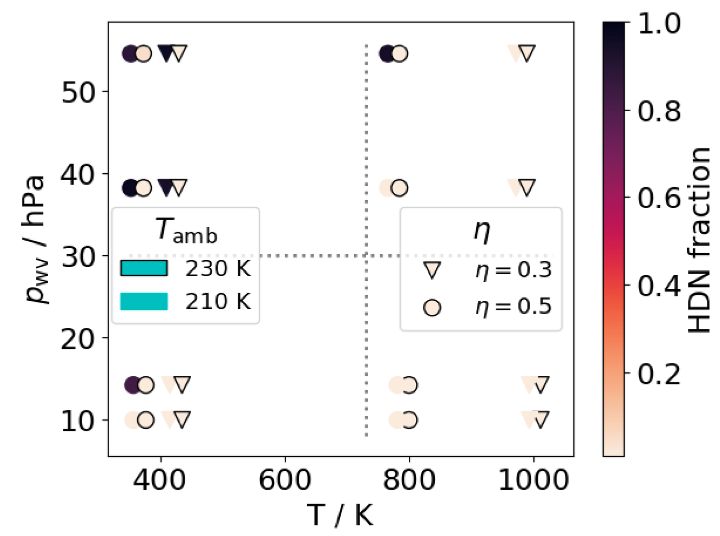
- Higher efficiency leads to more ice crystals
- Reducing the emission heat also increases N_{ice}
- N_{ice} can be reduced to zero for higher water vapor reduction (lower right corner)

N_{ice} depending on exhaust and ambient conditions



- HDN can increase N_{ice} for high supersaturation values inside the plume
- HDN process more likely to occur at low T_{amb}
- HDN impact difficult to predict quantitatively due to high non-linearity

Fraction of ice crystals formed by HDN



Summary

- Generalized contrail formation theory shows that mixing line formulation can also be used for very moist plumes
- Heat recuperation of H_2 fuel cell can trigger HDN process which leads to increased N_{ice}
- N_{ice} depends strongly on fuel cell settings → **Contrail properties can be influenced by technical design of fuel cell systems**
- Understanding ice crystal formation behind H_2 fuel cell propelled aircraft is important to assess the radiative effect of these contrails