

Review of A new ice crystal formation pathway in contrails generated by fuel cell propelled aircraft

This paper introduce a new ice crystal formation pathway for contrail formation behind a H2FC aircraft. It does so using the LCM code in a 1D configuration. First, the model is presented in good detail, then a sensitivity to the time step is done and a comparison with more complex CFD is done. Then a sensitivity analysis is performed for different parameters. Then the limitation of their model is discuss.

Overall the paper is well written and the work presented is interesting and there is many quality in the work. However the reference configuration for the H2FC dilution is not describe at all, which is disturbing considering the author discussion on the importance that the aircraft design. Moreover they say that the number of ambient aerosols can go up to 10^4cm^{-3} but they stop their sensitivity study at 10^3cm^{-3} . Since one of their conclusion in that if the humidity of the plume is high enough, ambient particles don't play a role, I suggest they also perform the "worst case" scenario for ambient particles. Finally, some of their hypothesis lack of justification, such as the fact they use a stationary nucleation rate at a time step at $5 \cdot 10^{-6} \text{s}$. For these reason I suggest major revision before publication. More detail below.

Major:

1. In line 108-113: you explain the objective of the paper, however it follows a description of the different kind of FC, some with low temperature exit (below 100°C) and some with high (above 100°C) temperature exit. Since your paper consist in including homogeneous droplet nucleation in your model during the dilution of the plume: Is this model relevant for low temperature exit where we may expect already liquid water considering the temperature? Or, do you think that this model will be needed by every kind of fuel cell?
2. Line 145 you use a mixing using the classical Schmidt appelman theory with correction to take into account cooling or recuperative strategies. I understand that this formula is published in one of your former work. However, I don't understand the proof of it, especially the overall efficiency of the propulsion system which is the work of trust divided by the energy extracted from combustion seems strange to me in the case of fuel cell. Let me explain myself, the trust from propeller comes from the rotative part, whereas the heat and water vapor are emitted by the fuel cell. Let's assume that I have the same fuel cell which will produce the same amount of electricity but two different propeller with different efficiency, my trust will be different but, since my fuel cell will certainly be in the fuselage and the propeller under the wing, the trust will not influence my exhaust. Then I expect my mixing line to be independent from the propeller. In fact if I imagine an aircraft with a fuel cell that will be used for another purpose, the contrail due to my fuel cell will be the same but the trust work is zero. Therefore in my opinion it should be more related to the thermal efficiency of the fuel cell which is defined by :

$$\eta_{th} = \frac{-W_E}{\dot{m}_F Q}$$

The proof goes as follow:

The mixing line is defined by :

$$G = \frac{P_{wE} - P_{wA}}{T_E - T_A}$$

Which assuming air in excess and that exhaust pressure is the same as the ambient (which should be close to the truth) can be written as :

$$G = \frac{E I_{H2O} P_A}{\epsilon C_E (T_E - T_A)}$$

Now $T_E - T_A = \frac{H_E - H_A}{m_A C_p}$ when assuming the same C_p from intake and exhaust and a low fuel flow compare to air flow. Now assuming (for fuel cell only) that the exhaust and intake velocity are the same, this leads to $T_E - T_A = \frac{H_{iE} - H_{iA}}{m_A C_p}$ with H_i the total enthalpy. The energy balance gives you that

$$H_{iE} - H_{iA} = m_F Q + W_E \text{ and then } T_E - T_A = \frac{Q(1-\eta_{th})}{C_E C_p}$$

Which gives at the end

$$G = \frac{E I_{H2O} P_A C_p}{\epsilon Q (1-\eta_{th})}$$

Then you probably could apply your corrections. A point, it is not necessary to assume the same velocities for exit and intake, you just need to introduce the turbojet thermal efficiency and you have the sum of the two efficiencies.

3. Line 286 you tell that $n = J \cdot dt \cdot A$ is the number of particles formed during 1 time step which is not homogeneous as n is a number per meter, the same question appears when you mention the numerical weigh of your SIP line 289.
4. You choose a threshold to account for nucleation based on the nucleation rate and then you look at the time step convergence by looking at the number of ice crystals. Since the number of particles formed depend on your time step, wouldn't it be easier to reach convergence with a threshold based on the number of particles formed during the time step? May be it is harder.
5. In part 3.3 you validate your results by comparing your LCM model with CFD codes which is great. However, it is really hard to follow: are grey curves different realization of different codes? Are those codes making the same hypothesis as you? Is there any experimental data to validate the CFD? Because, if you have a CFD code of an almost 1D case which use the same model as yours and that you read the CFD data, considering the rather low energy of nucleation compared to a high velocity flow, I expect your uncoupled strategy to give kind of the same results than the CFD. In my opinion this validate your implementation of the model, however it means nothing on the validity of the model by itself. So my question are you model using the same model as the CFD codes? And are these CFD validated on experimental data?

6. You use a nucleation rate, which assume a stationary state is a flow with quick variations. It should at least be mentioned and comment. In fact, considering the use of a 1D case and homogeneous unary nucleation, you could have compute the nucleation of particles with birth and death equations and compare your results with the nucleation rate which would really validate the approach.
7. You neglect the coagulation. Can you justify this with order of magnitudes?
8. In figure 5 you show results for ambient particle concentration of $10^2 / \text{cm}^3$ and different initial plume water content. Still for most humid plume conditions, HDN leads to 10^{10} ice crystal per meter of flight and seems to have reach a constant value except when ambient particles are the dominant nucleation pathway. If I look at the figure 5 of Zink 2025b which is your last reference, I see that for hydrogen combustion engine and ambient particle concentration of $10^2 / \text{cm}^3$ and very low oil emission, the ambient nucleation pathway reach values such as 5×10^{10} . Since you number of ice crystals due to ambient particles continue to grow at 0.3s and Zink computations seems to grow up to several seconds, you should probably should increase you computation time to see if HDN is still relevant after several seconds and if in fact, at the opposite of what you show in your study, that reducing the humidity of the plume will not leads to an increase of ice crystals. In the same way, you use the hypothesis of a rather clean and mean ($10^3 / \text{cm}^3$) atmosphere. Since you suggest values for ambient particles up to $10^4 / \text{cm}^3$, you should also run this case to conclude in every scenario.
9. As mentioned in line 510, HDN is very sensitive to small perturbations. Since a plume is an inhomogeneous flow with temperature and humidity variation even in its cross sections, is your 1D vision of the flow is enough to describe the HDN? What variation do you expect? This is mentioned in your discussion but is it possible to evaluate the error made?
10. In part 5.3 you mention the importance of aircraft design choice for fuel cell plume dilution. However, your reference dilution come from a CFD which is not shown in a configuration which is not describe. I'm sure that more information can be given such as the exhaust is under the wing or somewhere else. Since you mentioned issues with the boundary layer, and exhaust velocity, which case is describe by this CFD? Especially the CDF dilution is closer from the one of CFM 56 than the one of the exhaust, which should emulate a potential H2FC engine, which raise some questions.

Minor :

1. Line 81: you mentioned that only water are emitted by FC propulsion system. Since there is rotating part such as the propeller but probably also pumps, is these hypothesis will be true in practice?
2. Line 38-40 : It is not clear in the sentence if liquid droplet form during the mixing process or not. Since you compute the formation of these droplets I suggest to rewrite this sentence to make it a bit clearer

3. Line 65 : Is the relative humidity defined with respect of ice or liquid water?
4. Line 576 you mention that multitrajectory approach is not suitable for fuel cell. Can you give more detail on that?