Interactive comment on "Sensitivity of particle loss to the Kelvin effect in LES of young contrails" by Aniket R. Inamdar et al.

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The authors would like to thank Anonymous Referee #1 for his/her comments. The following are the authors' responses to the minor and major comments made by the referee:

Comment:

This is well written and clearly describes a study of how the Kelvin effect can influence the evaporative loss of particles in contrails. The approach and methods are laid out well, and the figures and tables are appropriate.

Response:

Thank You!

Minor Comments:

Range of Particle Sizes

Comment:

Somewhere in the text (probably page 3, third paragraph or so), the range of particles sizes used as inputs should be listed, and perhaps also in Table 1. This range appears in the figures, but the reader should be explicitly informed as well.

Response:

The initial size of particles is now mentioned in Sec. 2 and is also included in Table 1 of the revised manuscript.

Impact of Exhaust Enthalpy

Comment:

End of page 2 (line 20), it is stated "it is necessary to examine the impact ... [of jet exhaust enthalpy]". Yet in the conclusions, the result of this examination is a minor clause of conclusion 4 ("though the effect of exhaust heat is not seen to be persistent"). If it is considered necessary and important, the conclusion should be more prominent and more fully stated

Response:

Conclusion 4 in the revised manuscript is modified to explain in greater detail the influence of exhaust enthalpy.

Major Comment:

Comment:

While the impact of the Kelvin effect on particle loss is studied here, even the results shown in this paper indicate that the potential impact on initial particle growth is much more significant. Looking at figure 1 b, the steep slopes for particles in the 10 - 100 nm range show that much that is going on is sensitive to the early particles sizes (which start at 10s of nm for aircraft PM emissions). Further, comparing Figure 2 a and b shows that the initial particle number has a larger impact than the variation in Kelvin parameter. The initial size and number is defined by competition for water vapor by the initial condensation nuclei (soot particles). Thus, if the Kelvin effect is important for evaporative loss, it also will affect the initial condensational growth. Figures 1 and 2 strongly suggest that the initial number and size, as determined by Kelvin effect mediated competition for water vapor are much more important than the more subtle effects of Kelvin effect on evaporative loss.

My opinion is that the authors should have noticed this, and extended their study to understand the more important end (the initial size and number) of where the Kelvin effect influences things. I don't take issue with the effect of loss, but the paper gives the strong impression that this is the important consequence, when the results they present suggest otherwise. At the very least, the potential for even bigger Kelvin effects on initial particle properties (size and number) must be clearly stated. And then state that these big effects on initial properties also affect the loss that they are studying (per Figs 1 and 2) and this must be explained fully. But really, it is my opinion that to be scientifically honest, the authors should go back an include a study of the impact of the Kelvin effect on initial condensational growth and have a more complete package, since I think they have focused on a secondary process which is is strongly influenced by what they have left out.

My recommendation is to reject this paper, and the authors should do the complete study that includes the influence of Kelvin effect on the initial condensational growth. If the editor finds this paper's limited scope acceptable, I would strongly maintain that it should only be accepted if the limitations of leaving out the likely dominance of the Kelvin effect on condensational grown are clearly discussed and the results of this study and how they are used are caveated appropriately. But I would prefer that they go back and explore the broader impact of the Kelvin effect by exploring how it affects initial size and number via condensational growth as well as evaporative loss.

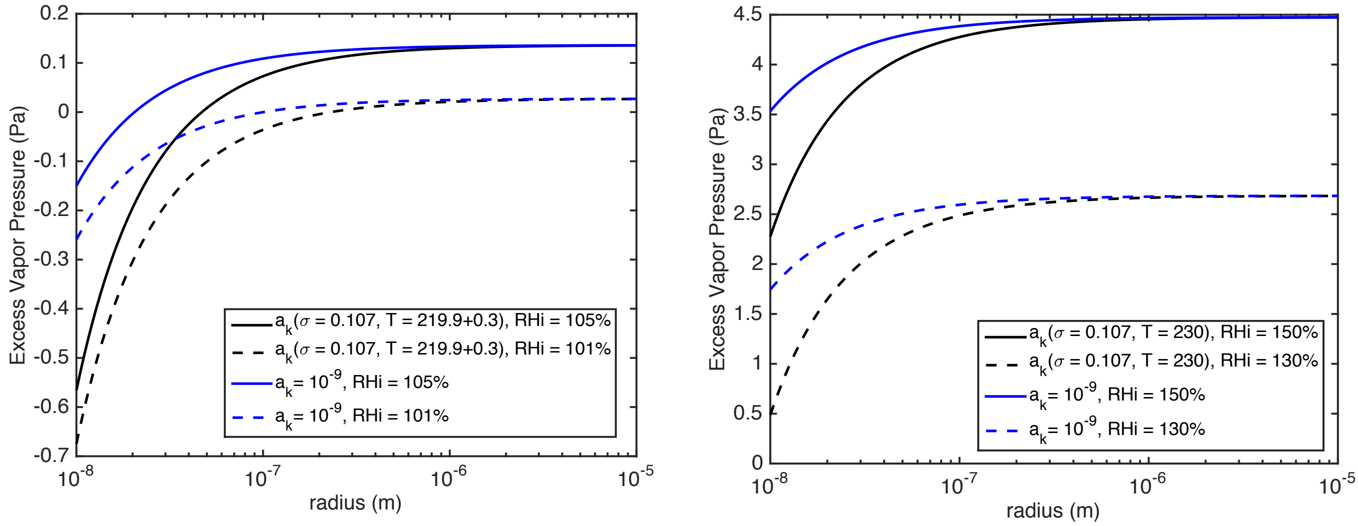
Response:

Here, the referee suggests that since we saw a large sensitivity to the Kelvin effect in the vortex phase, we should also expect the same sensitivity, if not more, in the jet phase and examine that phase too. We thank the referee for this insightful comment. However, the jet phase is very unlikely to be as sensitive to the Kelvin effect because the conditions experienced by the plume are very different in the jet phase than in the vortex phase. The jet phase dynamics are an order of magnitude faster than the vortex phase and the plume experiences strong ice supersaturation in the jet phase as against near-saturation in the vortex phase.

In the present study, we observe that the plume temperature remains nearly constant and warmer than ambient during the vortex phase (our Figure 1(a,Top)) and simultaneously the plume RHi remains only marginally supersaturated (close to 100%) (Naiman et al., 2011; Paoli and Shariff, 2016; Lewellen et al., 2014). At near-saturation, even small changes in the value of $a_k(\sigma,T)$ (our Eqn. 1), can result in dramatic increase in the apparent sub-saturation experienced by small particles (Figure 1(b, Bottom)). This is sustained for the entire period of vortex phase ($\mathcal{O}(10s)$) resulting in large and irreversible loss of small particles.

The jet phase has been extensively studied by Karcher et al. (2015); Wong and Miake-Lye (2010); Karcher and Yu (2009); Yu and Turco (1998) to name a few. In early jet phase, the plume temperature falls rapidly and consequently the RHi increases to very high values (peak $\sim 200\%$) due to the presence of vapor emitted by the engine (see Figure 1(b) in Karcher and Yu (2009)). The Kelvin correction factor, $\mathbf{\Phi}(r, a_k(\sigma = 0.107, T = 230))$, for $r \in \{5, 10\} nm$ is calculated to be $\{1.55, 1.25\}$ respectively. We see a $\sim 55\%$ increase in apparent saturation vapor pressure for a 5nm particle. Thus, at such high plume RHi ($\sim 200\%$), particles even of sizes 10's of nm, will still experience supersaturation after Kelvin correction, albeit weakened. In the above example, the 5nm particle at $T = 230K$ and $RHi = 200\%$ will still experience an excess vapor pressure of $\sim 4Pa$ and grow in size.

To demonstrate that even particles of size $\mathcal{O}(10^{-8}m)$ experience positive excess vapor pressure, we have attached a figure plotting the excess vapor pressure over the Kelvin-corrected saturation vapor pressure similar to our Fig. 1(b, Bottom) but with RHi $\in \{150\%, 130\%\}$ and T = 230K. Experiencing a net positive excess vapor pressure, the particle size quickly increase to an almost unimodal size PDF around $\sim 1\mu m$ as seen in Wong and Miake-Lye (2010). Our initialization of particle number and size is consistent with the results of such studies (compare our Figure 3(b) and Figure 2(e) in Karcher and Yu (2009)).



(a) Near-Saturation

(b) Strong Supersaturation

Figure AR 1. Excess Vapor Pressure - (a) Representative of plume in vortex phase, (b) Representative of plume in early jet phase

We strongly contend that the weakening of the supersaturation due to Kelvin effect in the jet phase will have little impact on the particle number and size. From Figure 1(b) of Karcher and Yu (2009), we infer the time for uptake of vapor emitted by the engine to be $\sim 0.2s$ and a similar time scale can be inferred from Wong and Miake-Lye (2010). Consider an activated soot particle of initial size 10nm, similar to the initialization in Karcher and Yu (2009); Wong and Miake-Lye (2010), experiencing the following externally specified RHi and T variation as inferred from Figure1(b) of Karcher and Yu (2009):

$$RHi = \begin{cases} 200 - 100 \times \frac{\log(\frac{t}{0.1})}{\log(3)} & t \in [0.1, 0.3]s \\ 100 & t \in [0.3, 0.5]s \end{cases} \quad AND \quad T = 235 - 15 \times \frac{\log(\frac{t}{0.1})}{\log(5)} \quad t \in [0.1, 0.5]s \tag{1}$$

Using Eqn. 9 from Naiman et al. (2011) we can estimate the growth of this particle with and without Kelvin effect and this is shown in Figure AR 2. From these plots, we may expect in the jet phase, the initial rapid growth of particles to sizes of $\mathcal{O}(1\mu m)$ due to very high plume RHi to render the Kelvin effect insignificant. This simple analysis leads us to conclude, different modeling of the Kelvin effect may not affect our simulation initialization (a few seconds behind the aircraft) in any significant way. An exact quantification, if necessary, of how different treatments of the Kelvin effect may affect the uptake of vapor in the jet phase may be left to studies equipped with the simulation framework to examine the chemically reactive and compressible dynamics of the early jet phase, which the current simulation framework is not capable of resolving. But, given the above reasoning, we believe this computationally expensive exercise may yield insignificant results.

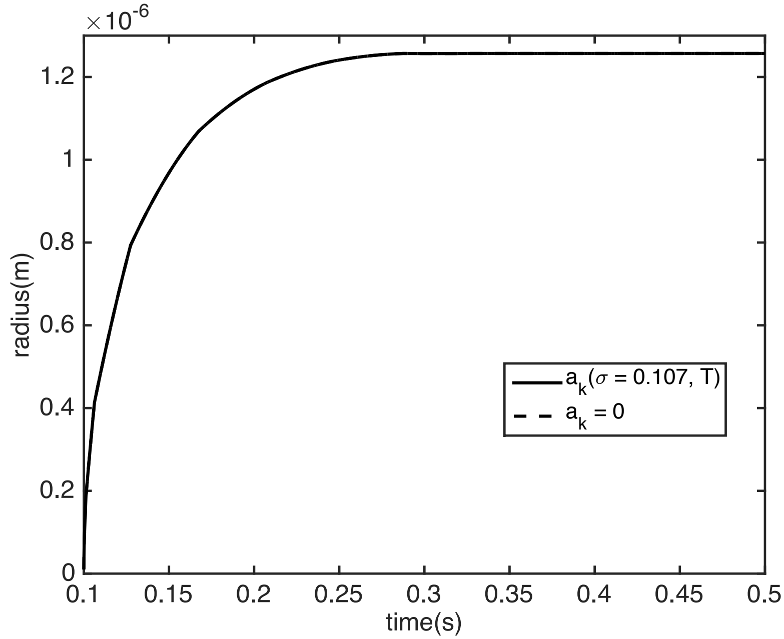


Figure AR 2. Model Jet Phase Ice Growth

To reiterate, different treatment of the Kelvin effect has a large impact on evaporative loss of particles in the vortex phase as the plume experiences RHi close to saturation and nearly constant temperature warmer than the ambient for 10s of seconds. Kelvin effect is very unlikely to have a significant impact on the jet phase as the RHi in the jet phase is substantially higher than saturation and the time scale of vapor uptake in the jet phase is an order of magnitude faster than the time scale of vortex dynamics.

This discussion on the Kelvin effect in the jet phase has been included in the revised manuscript as an appendix.

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