Issues Related to Saturated Plumes in the AERMOD System

Overview of Issue

Recently published literature has advanced the hypothesis that wet or moist plumes are not properly characterized in AERMOD and other dispersion models. This is particularly important given the rise in the use of "wet" scrubbers at very large industrial boilers, such as electrical generation units.

Per a recent Atmospheric Environment article[1], the authors assert that…

"in many cases for moist plumes, the effect on plume rise can be significant due to heat of condensation and should be accounted for, particularly for emission sources that operate flue gas desulphurization equipment, or scrubbers, designed to remove several pollutants from combustion plumes. The scrubbing process acts to partially or fully saturate exhaust gases while minimizing any liquid "drift" emerging from the scrubber to minimize chemically erosive processes. This process acts to cool the plume relative to the unscrubbed exhaust, resulting in a reduction of plume rise. However, the moist plume exits the stack and the heat of condensation released by the liquid water particles acts to make the plume gases warmer, giving the plume additional buoyancy. Some of this buoyancy is lost as the droplets evaporate on mixing, but a net gain in plume rise is realized from the heating/cooling process. The largest net rise is realized for the situation where the ambient air itself is near saturation."

As described in the Atmospheric Environment article, AECOM develop the "AERMOIST" source characterization preprocessor to account for this initial condensation of the plume moisture which liberates the heat of condensation as the plume exits the stack and cools in the presences of ambient air. This additional heat increases plume buoyancy during the initial rise phase and alters the downwind dispersion of the plume and alters the model predicted concentration impact in a manner consistent with enhanced dispersion and subsequently reduces some of the near-field over predictions observed with the modeling of moist plumes with AERMOD. It should be noted that the AERMOIST preprocessor is adjusting the source characteristics to indirectly alter AERMOD's formulation to account for the enhanced thermodynamics of moist plumes.

Current Implementation in AERMOD

AERMOD formulations are based on an essentially dry plume and does not account for any additional heat released due to condensation in the plume. So from a theoretical and physical perspective, there is merit to the hypothesis stated above, particularly with moist plumes. The approach explored with the AERMOIST preprocessor indirectly alters the AERMOD formulation to account for the thermodynamic differences related to moist versus dry plumes and demonstrated model performance improvements in a few cases. EPA believes a direct update to the AERMOD model formulation to account for the enhanced thermodynamics associated with moist plumes would provide a more appropriate and scientifically defensible long-term path forward to address this issue.

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[1] Robert Paine, Laura L. Warren, and Gary E. Moore. Source characterization refinements for routine modeling applications. Atmospheric Environment, Volume 129, March 2016, Pages 55-67.

Summary of Current Literature or Research

The AERMOIST tool is documented in the aforementioned Atmospheric Environment article, which includes references to other peer reviewed publications that support assumptions and aspects of the characterization incorporated into the AERMOIST preprocessor. At this time, there is very limited information available for supporting the scientific basis and additional AERMOD model performance evaluation based on the application of the AERMOIST preprocessor. As detailed below, there have been limited situations in which EPA regional modelers have evaluated specific applications of the AERMOIST preprocessor. Additionally, there is no known AERMOD model formulation research or development specific to moist plumes.

Paine et al., 2016

AERMOIST is based on a moist "plume rise" model, IBJpluris, that has been evaluated with aircraft measurements of moist plumes in the peer-reviewed literature. AERMOIST uses IBJpluris to determine hourly adjustments in plume rise and then modifies stack temperatures for input to the dry plume rise model in AERMOD to force simulation of increased plume rise. The AERMOIST model modifies CEM measured data prior to input to the AERMOD system.

As presented in the aforementioned Atmospheric Environment journal article…

> "A validated, moist plume rise model called "IBJpluris" has been found to accurately predict the final rise of a moist plume (Janicke and Janicke. "A three-dimensional plume rise model for dry and wet plumes." Atmos. Environ., 2001.) and can be used to complement the dispersion modeling process when moisture content can be a significant factor. The IBJpluris model formulation includes a general solution for bent-over moist (initially saturated) chimney plumes (Janicke and Janicke, 2001). The model was reviewed by Presotto et al. (Presotto, Bellasia, and Bianconi, 'Assessment of the visibility impact of a plume emitted by a desulphuration plant.' Atmos. Environ., 2005.), which indicated that despite a number of entrainment formulas available, IBJpluris possessed the physical capability of representing the impacts of heat of condensation on symmetric chimney plume rise. The Presotto et al. (2005) paper also reported field evaluation results for the IBJpluris model involving aircraft measurements through moist plumes emitted by stacks and cooling towers. Therefore, IBJpluris was selected as the core model for developing and applying a simple adjustment method to the standard Briggs (1975) plume rise formula used by AERMOD to account for thermodynamic modification of plume rise…
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> …This is done by performing IBJpluris model runs for both the actual moist plume and a dry plume so that the adjustments for the difference can be made and transferred to hourly plume input data for models such as AERMOD. By assuming the ambient environment that the plume rises through is identical for both a dry and wet plume, a reasonable assumption is that the ratio of the wet to dry plume rise for IBJpluris can be used to adjust the dry dispersion model plume rise to a moist plume rise prediction. The approach assumes that this scaling ratio is independent from changes in wind speed and stability, although the variations in rise may be rather large. This assumption is reasonable since the rise is functionally related to the sum of exiting buoyancy and vertical momentum fluxes and the difference between dry and moist rise depends mainly on buoyancy, which is primarily temperature- and relative humidity-dependent…

…In AERMOIST, the IBJpluris model is exercised in both dry and wet mode for each range and an array of temperatures and humidity over the range of possible values, β(Ti,RHj) ratios, is saved for each stack that is modeled and are used to estimate the model adjustment coefficients. The β(Ta,RHa) are used to estimate the equivalent hourly plume temperatures for input to the dispersion model for each hour of emissions. By modifying only the plume temperature, multiple sources can be included in the model run, each with their own series of equivalent hourly plume temperatures. Dry plumes can also be modeled with standard, constant input data."

The Atmospheric Environmental journal article did not offer any model performance evaluation of AERMOIST. It only offered an example on a typical saturated, scrubbed power plant to demonstrate the impact on plume temperature and downwind plume height. In this sensitivity analysis, there was a 15K rise in plume temperature and then between 10 and 15% increase of plume height at 2000m downwind based on a relatively dry or moist ambient environment.

Application of AERMOIST in Region 3 and 6 SO_2 Modeling Situations

Both Regions 3 and 6 have evaluated the application of AERMOIST for SO_2 related modeling situations in their respective Regions. In both evaluations AERMOIST has had both anticipated and somewhat unexpected results that leave a level of concern on the broad application of AERMOIST without a further and more comprehensive model performance evaluation of the AERMOIST preprocessor.

In the Region 3 case, the Brandon Shores power plant was modeled with and without AERMOIST. AERMOIST was found to have an average temperature adjustment to the plume temperature of 10 to 20 K, which is reasonable on the surface. However, there was also a percentage of adjustments exceeding 50 K with a maximum adjustment of 72 K. Raising the plume temperatures in AERMOD via AERMOIST appeared to generally raise the height of the maximum model concentration (surrogate for plume height) under stable conditions though it was not uniform. The height increase was in the 10 to 15 % range. AERMOIST appeared to have little impact on plume height during unstable (mixing) conditions. It was found through the Brandon Shore evaluation by Region 3 that the application of AERMOIST also appeared to lower the overall maximum model concentrations within the raised plume. So, there is possible more going on in the adjustments than displacing the plume.

In the Region 6 case, the Martin Lake power plant was modeled with and without AERMOIST along with another preprocessor, AERLIFT. In the Martin Lake evaluation, similar impacts of plume temperature increases in the 15 K range were noted. Also, more robust or extreme adjustments were noted of just over 100 K in several instances. Overall, there was on the order of a 15% increase in buoyancy of the plume from just the AERMOIST adjustment, which was very similar to that of the Brandon Shores case. Complicating the Martin Lake evaluation was the application of AERLIFT that had much more dramatic temperature adjustments to the plume, on the order of 200 K in some instances. When combined the two preprocessor had maximum impacts of approximately 300 K, which is completely unrealistic.

Considerations for Updates in Model

An appropriate adjustment to the plume temperature is theoretically plausible to account for enhanced plume velocity due to the thermodynamics of wet or moist plumes when modeled with the AERMOD Modeling System. AERMOIST is based on peer reviewed literature that has some basis in making the appropriate adjustment, albeit indirectly.

The limited sensitivity analysis in the AECOM journal article and the evaluations in Region 3 and 6 demonstrate an average plume temperature adjustment of 10 to 20 K and plume height increase of approximately 15%. However, the Region 3 and 6 evaluations have presented situations where the adjustment to plume temperature has been between 50 and 100 K in some limited cases, which is a significant temperature adjustment that deviates from the Atmospheric Environment article and associated references. Region 3 found indications that the downwind modeled concentrations may have been lowered within the raised plume. Additional investigation is necessary to better understand the impacts of the AERMOIST preprocessor on modeled concentrations within the moist plume and not just at specific ground receptor locations nearby to the source in question. Region 6 has also stated that when the liquid water evaporates downwind in the plume, it reduces the buoyancy of the plume by the same amount of the initial increase. This reduction should then act to depress plume rise, but it is theorized to occur when the plume is more dilute and may have approached reached final rise – thus minimizing the effect. Both Region 3 and 6, as well as OAQPS, have expressed some concern about the use of relative humidity levels at typical observation (2m) height to be representative of relative humidity levels of the ambient air at stack height (often 100m to 200m).

As a result of the EPA regional office findings, EPA believes that there are outstanding questions about the broad application of the current AERMOIST source characterization preprocessor without a comprehensive model performance evaluation of AERMOD with AERMOIST for a variety of sources and locations, *e.g.*, flat and complex terrain. Ideally, this comprehensive model performance evaluation would be included in a subsequent peer-review journal article(s). Additionally, both of the cited journal articles in the Atmospheric Environment article (Janicke and Janicke, 2001 and Presotto et al., 2005), as presented above, need further review and consideration for potential future AERMOD formulation enhancements to directly account for the different dispersion characteristics of moist plumes.

References

Paine, R., Warren, L., and Gary E. Moore. (2016). Source characterization refinements for routine modeling applications. Atmospheric Environment, Volume 129, March 2016, Pages 55-67.

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Presotto, L., Bellasia, R., and R. Bianconi. (2005). Assessment of the visibility impact of a plume emitted by a desulphuration plant. Atmospheric Environment, Volume 39 (4), Pages 719-737.