

## Design and Evaluation of a Mini Catalytic Stripper

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The principle of operation of the catalytic stripper (CS) is to evaporate semi-volatile particulate matter and to oxidize the resulting gas phase compounds. Inorganic compounds such as sulfate are chemically absorbed onto the washcoat of the catalyst. This approach differs from other methods such as the thermal denuder and the volatile particle remover (VPR) that remove gas phase material via physical adsorption or rely on dilution to prevent re-nucleation.

The objective of this project was to design, build, and evaluate a CS that was optimized for particle loss and hydrocarbon and sulfate removal efficiency and to compare results with the VPR technique. The substrate geometry was configured to maximize removal and minimize solid particle loss; design values, calculated performance and a photograph of the catalytic core are shown below. Additionally, the catalytic core, heating source, and cooling region have been integrated into a compact package. This allows the CS to serve as a convenient and portable aerosol-conditioning inlet for any instruments that requires an inlet flowrate of 1.5 L/min. The performance of the CS was compared with the AVL APC that is used to determine compliance with the European PMP solid particle number standard. The AVL APC uses an evaporation tube to evaporate solid material and dilution to reduce gas phase nucleation. The AVL instrument is an example of a commercially available volatile particle remover.

Design specifications of the UMN mini CS and photograph of the prototype unit.

Core length	3.8	cm
Core width	1.7	cm
Cell density	600	cells/in
Cell wall thickness	2.5	mil
Flowrate	1.5	L/min
C <sub>40</sub> H <sub>82</sub> removal	99.5	%
50% cut off size	7	nm



To evaluate solid particle penetration through the CS and AVL APC, solid silver nanoparticles were generated using an evaporation/condensation technique. The instrument was challenged with size selected silver particles while up and downstream concentrations are measured simultaneously. CS results indicated that the measured 50% lower particle cutpoint

was near the predicted value (10 vs. 7 nm). The slightly reduced performance may be attributable to maldistributed or recirculating flow in the inlet. The AVL APC performed similarly with a 50% cut point of about 15 nm.

Two techniques were used to generate sulfuric acid challenge aerosols. First, particles were generated by heating sulfuric acid liquid and entraining the vapor. Sulfuric acid particles form when the hot vapor is diluted and cooled. For mass concentrations ranging from 1 to 1,000  $\mu\text{g}/\text{m}^3$ , the CS removed >99% of sulfuric acid by mass. However, for all experiments, there was a residue of very small (~10 nm) particles downstream of the CS. Additional tests demonstrated these particles were solid. The size and concentration of the residue depended on whether water vapor was used to humidify the vapor entrainment air stream. Results suggested that the residue concentration downstream of the CS was partially due to contamination in the water used for humidification, but there is still some residue when no water vapor is used.

An alternative generation technique was used to further investigate the potential sources of the residue particles. In this technique, particles were generated by passing sulfur dioxide collected from a permeation tube through an oxidation catalyst heated to 400 °C. Sulfuric acid particles form when the hot gas was diluted and cooled. Preliminary results showed that solid residue particles were still present downstream of both the CS and AVL APC. Additional experiments were conducted to determine the performance limits of the CS and APC. For these experiments a second CS was operated downstream of the test CS and APC. The second CS was used to distinguish between solid residue particles and semi-volatile sulfuric acid particles that were the result of the nucleation of sulfuric acid vapors that break through the test instrument. Results showed that the maximum upstream mass concentration before renucleation occurred downstream the APC was ~ 1  $\text{mg}/\text{m}^3$ . The actual concentration used to challenge the VPR was ~100  $\mu\text{g}/\text{m}^3$  because the challenge aerosol is first diluted by 10:1 by a heated rotating disk dilutor before entering the evaporation tube. The CS removed 10  $\text{mg}/\text{m}^3$  before nucleation was observed downstream. No dilution is used with the CS.

Additional experiments were conducted to evaluate the hydrocarbon removal performance of the CPC and AVL APC. The instruments were challenged with dioctyl sebacate particles ( $(\text{CH}_2)_8(\text{COOC}_8\text{H}_{17})_2$ ) that were also generated using an evaporation/condensation technique. Generated particles that were size selected at sizes of 30, 40, 50, and 60 nm were used to challenge the CS and the APC. Results indicated that both the CS and APC could fully remove (efficiency of 100.0%) concentrations of >10,000  $\text{part}/\text{cm}^3$  for all particle sizes, including those below 23 nm, which meets and exceeds the removal requirements of the PMP method. Experiments using generated particles with no size selection demonstrated both the CS and APC could also fully remove 80  $\mu\text{g}/\text{m}^3$ . Limited evaluations were made with tetracontane particles that were 100 nm in size. This was regarded as a worst case scenario: very large particles with very low volatility. Results showed that these particles did not fully evaporate in the CS but they did in the AVL APC. This may be the result of the added benefit of the heated primary dilution in the AVL APC that aids in evaporation.

In conclusion, we have shown that the newly designed mini CS has a lower cutpoint of 10 nm, making it suitable to aid in the evaluation of solid particle size and concentration < 23 nm. This may be particularly relevant to the measurement of solid particle emissions from gas turbine engines, where particles tend to be much smaller than those from compression ignition engines. In addition, the CS also removes gas phase hydrocarbon contamination that can lead to additional issues. This is important in light of recent results that suggest contamination of condensation particle counter wicks with unburned automotive exhaust gas vapors is possible

and such contamination leads to performance drift. In addition to removing gas phase contamination, the CS shows a clear particle-removal performance benefit; it can remove  $\sim 10 \text{ mg/m}^3$  of sulfuric acid particles compared with  $\sim 100 \text{ }\mu\text{g}^3$  for the VPR method but results are difficult to interpret due to residue particles downstream of the CS and APC. Light hydrocarbon particles are effectively removed by the CS, but 100 nm heavy hydrocarbon particles do not fully evaporate; this could be mitigated by raising the CS temperature or by adding heated dilution air upstream. Additional experiments are planned to further elucidate the nature of the solid particle residue observed during sulfuric acid particle evaluations and to better understand the evaporation and removal of very heavy hydrocarbons in the CS.

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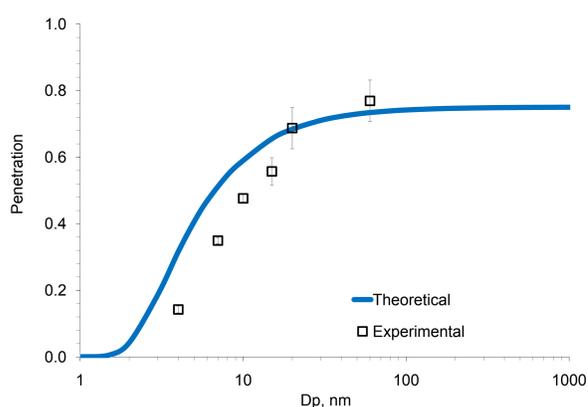
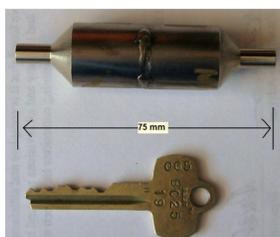
## Introduction

The principle of operation of the catalytic stripper (CS) is to evaporate semi-volatile particulate matter and to oxidize the resulting gas phase compounds. Inorganic compounds such as sulfate are chemically absorbed onto the washcoat of the catalyst. This approach differs from other methods such as the thermal denuder and the volatile particle remover (VPR) that remove gas phase material via physical adsorption or rely on dilution to prevent renucleation.

The objective of this project is to design, build, and evaluate a CS that is optimized for particle loss, hydrocarbon and sulfate removal efficiency, and to compare results with the VPR technique.

## CS Design and Performance

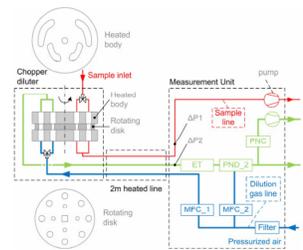
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Core width	1.7	cm
Cell density	600	cells/in
Cell wall thickness	2.5	mil
Flowrate	1.5	L/min
C <sub>40</sub> H <sub>82</sub> removal	99.5	%
50% cut off size	7	nm



Solid particle penetration data shows CS has a 50% cutpoint at ~10 nm. Thermophoresis results in roughly 30% loss for all particles independent of size.

## AVL APC

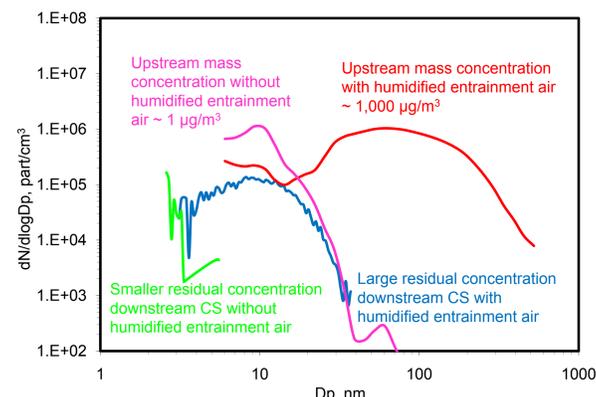
The AVL APC used to determine compliance with the European solid particle number standard uses an evaporation tube to evaporate semi-volatile material and dilution to reduce gas phase nucleation.



## Results – Sulfate Aerosols

### Particle generation by evaporation / condensation

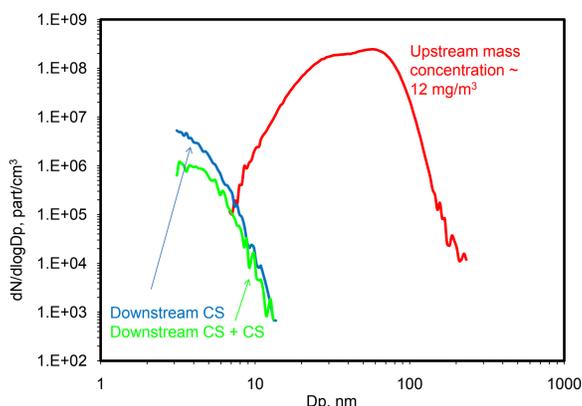
Particles were generated by heating sulfuric acid liquid and entraining the vapor. Sulfuric acid particles form when the hot vapor is diluted and cooled.



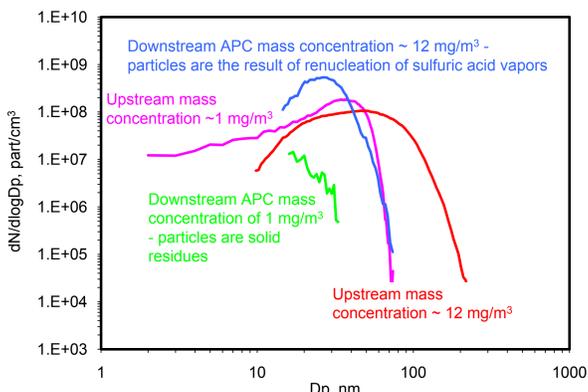
The residue concentration downstream of the CS is partially due to contamination in the water used for humidification.

### Particle generation by oxidization of sulfur dioxide gas

Particles were generated by passing sulfur dioxide collected from a permeation tube through an oxidation catalyst heated to 400 °C. Sulfuric acid particles form when the hot gas is diluted and cooled.



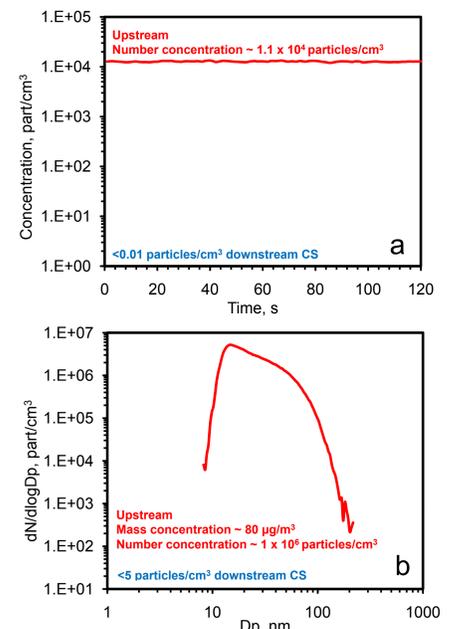
Two CS units placed in series demonstrate that the residue particles are solid.



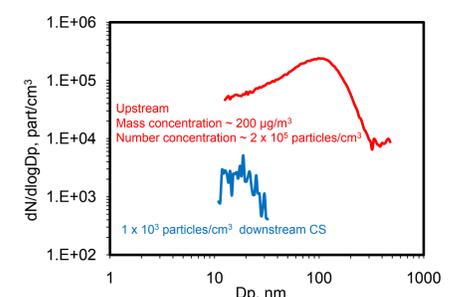
Maximum upstream mass concentration before renucleation occurred downstream APC was ~1 mg/m<sup>3</sup> or ~100 µg/m<sup>3</sup> after heated primary dilution.

## Results – Hydrocarbon Aerosols

Particles were generated by heating dioctyl sebacate liquid and separately, solid tetracontane. Entrained hydrocarbon vapors form particles when diluted and cooled.



Figures above show CS challenged by (a) 30 nm DOS particles, and (b) the full distribution corresponding to 80 µg/m<sup>3</sup>.



Preliminary results show ~100 nm tetracontane particles do not fully evaporate in the CS (figure above) but do in the AVL APC (not shown).

## Conclusions

- The CS has a lower cutpoint of 10 nm, making it suitable to aid in the evaluation of solid particle size and concentration < 23 nm.
- The CS shows a clear particle-removal performance benefit; it can remove ~10 mg/m<sup>3</sup> of sulfuric acid particles compared with ~100 µg/m<sup>3</sup> for the VPR method but results are difficult to interpret due to residue particles downstream of the CS and APC.
- The CS also removes gas phase hydrocarbon contamination that can lead to additional issues.
- Light hydrocarbon particles are removed effectively by the CS, but 100 nm heavy hydrocarbon particles do not fully evaporate; this could be mitigated by raising the CS temperature or by adding heated dilution air upstream.

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## References

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