Total Temperature Measurements Using a Rearward Facing Probe in Supercooled Liquid Droplet and Ice Crystal Clouds

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Outline

» Background

» Probe & Facility

» Thermal model

» Test Campaign

» Results

» Conclusions

Background and Motivation

- **Engine Icing**
  - Performance loss: rollback, surge, flameout, and even internal engine damage
  - Partial melting and refreeze of ice inside engine core (Mason et al., 2006)
  - Ingestion of ice crystals and aggregates, mixed-phase droplets, or supercooled liquid droplets
  - Need to better understand the conditions and properties that lead to engine icing.

- **Simulation and analysis (physical and computational, and modeling)**
  - Test facilities (PSL, NRC, …)
  - Thermal and computational models and analysis

- **Probes**
  - Multiple probes (aerothermal probes and ice cloud characterization probes and techniques)
  - Total temperature
    - ➢ Traditional total temperature probes (vented forward facing)
    - ➢ Heated total temperature probes (De-Ice total temperature probe, Goodrich)
    - ➢ Rearward facing (developmental)

Background

Total temperature (thermal and inertial):

$$T_0 = T + \frac{V^2}{2C_p}$$

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M$$

Total temperature relevance –

- Thermal interaction between the icing cloud and air flow
- impinging particles contribute to kinetic heating effect (Gent et al., 2000)

Measurement considerations–

- Temperature sensor accuracy
- Incomplete recovery of total temperature
  - Thermal surfaces (sources and sinks)
  - Flow effects (viscous losses)
  - Debris contamination, including icing and ice ingestion

Background

Recovery factor and correction

$$Y = \frac{T_r - T_s}{T_0 - T_s} \qquad \eta = \frac{T_0 - T_r}{T_0} \quad , \qquad \eta = f(M)$$

(T_r – recovery temperature ~ measured temperature)

For ice cloud interaction at M = const. ,

$$\frac{T_{0,1} - T_{r,1}}{T_{0,1}} = \frac{T_{0,2} - T_{r,2}}{T_{0,2}} \qquad T_{0,2} - T_{0,1}\left(\frac{T_{0,2}}{T_{0,1}}\right) = T_{r,2} - T_{r,1}\left(\frac{T_{0,2}}{T_{0,1}}\right)$$

1- before ice cloud
2- during ice cloud

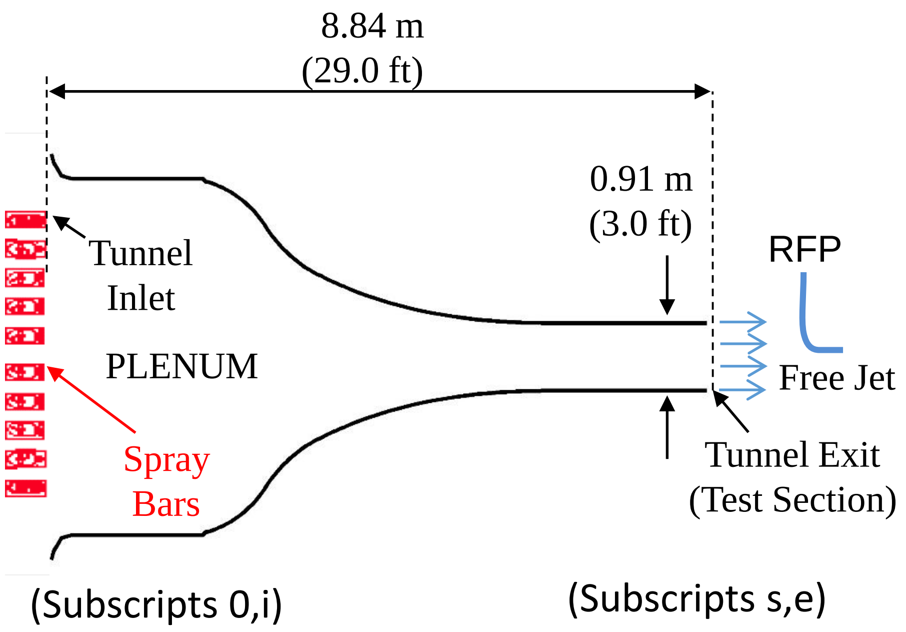
For small temperature changes around freezing,

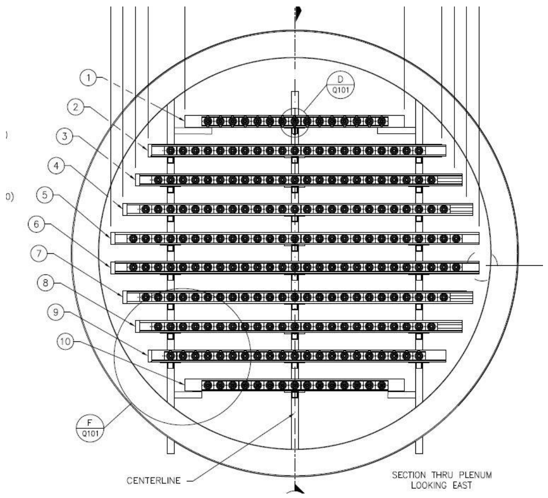
$$\Delta T_0 \approx \Delta T_r$$

Propulsion Systems Laboratory (PSL)

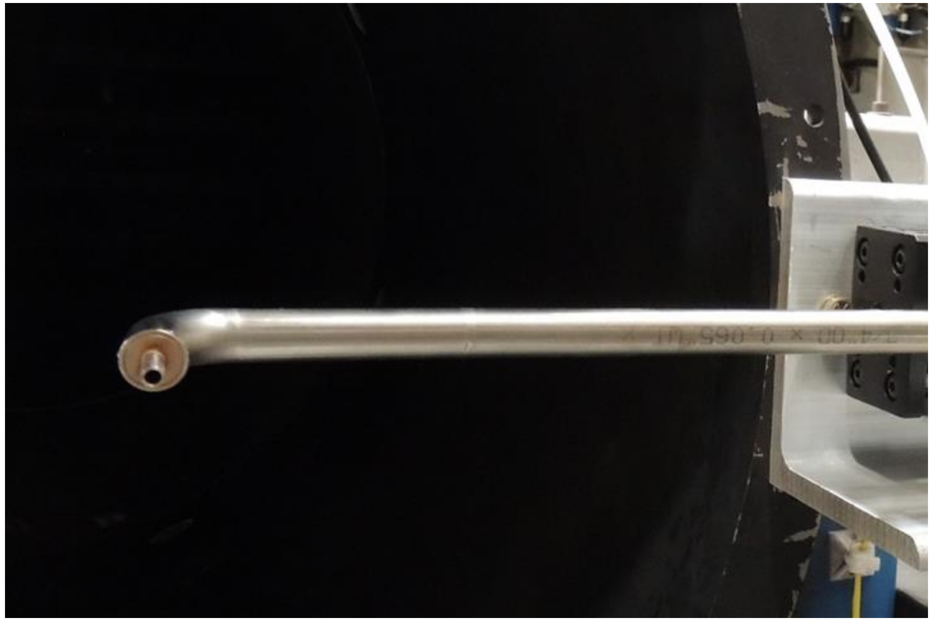
Tunnel Capability

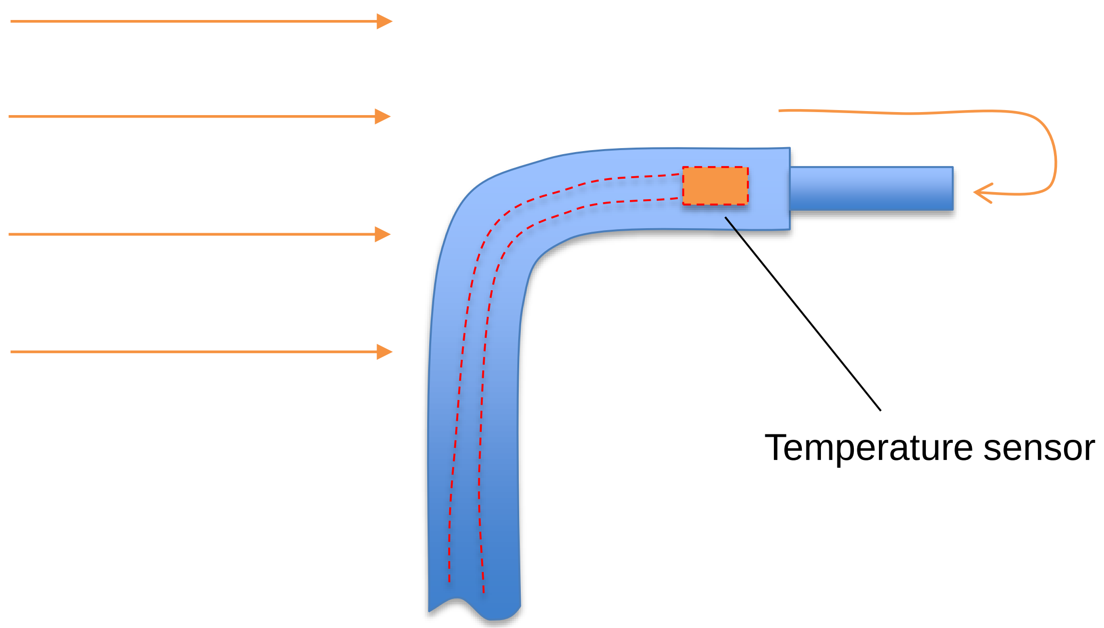
- Freeze out liquid cloud
- 12 parameters can be varied
  - P, V, T_{air}, T_{water}, RH, MVD, TWC, Water Type, Nozzle Pattern…





Rearward Facing Probe (RFP)



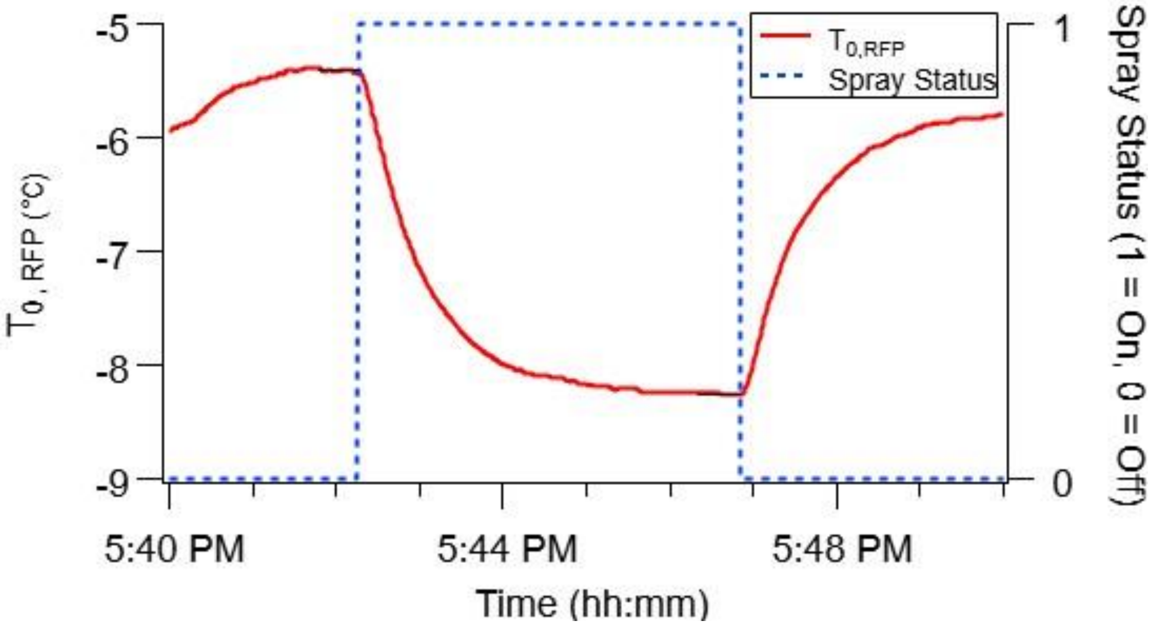


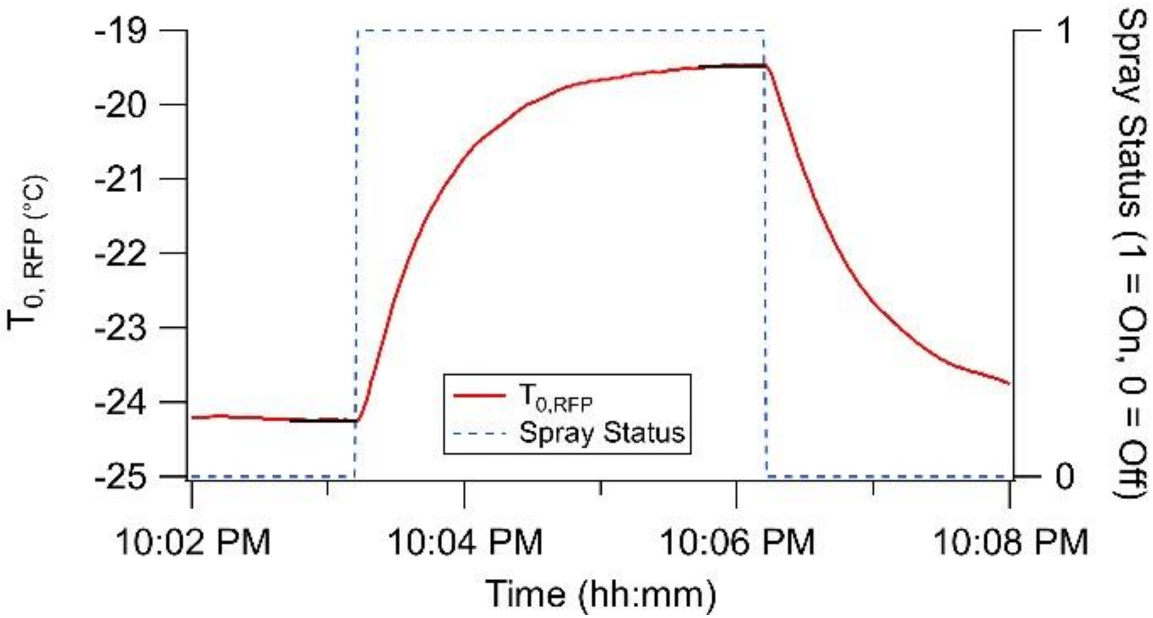
Data Logging

Gas Analyzer

Rearward Facing Probe

Total Temperature signals

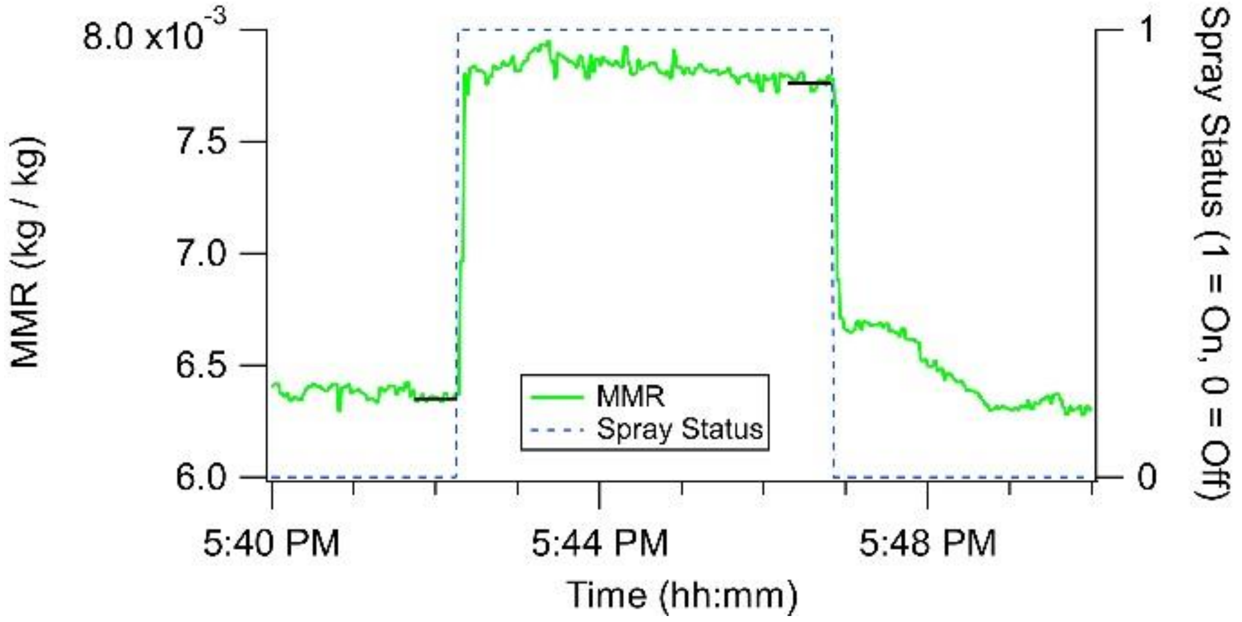




Rearward Facing Probe

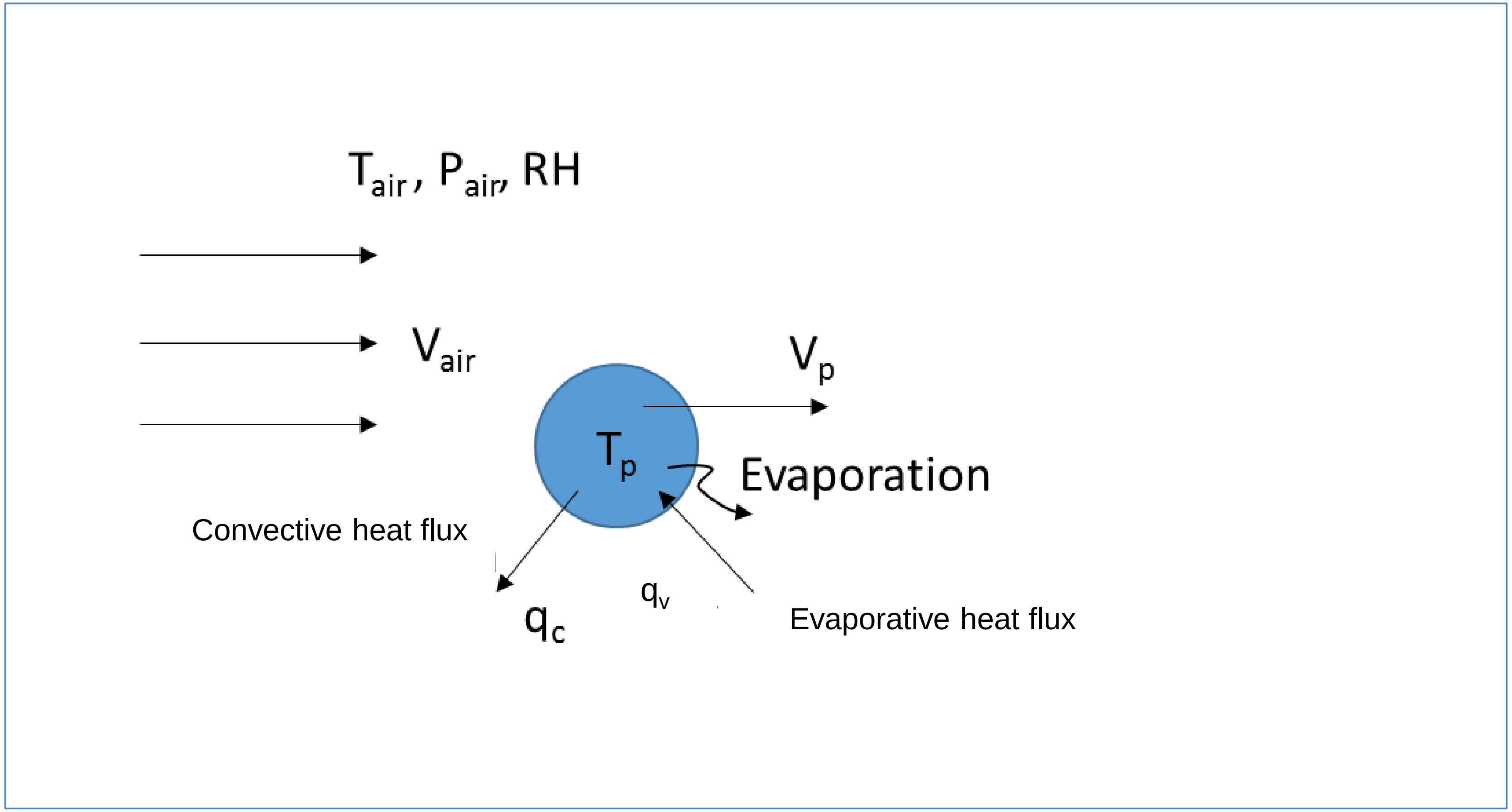
Humidity signal

Sampled flow → Gas/Humidity Analyzer



Thermal Model

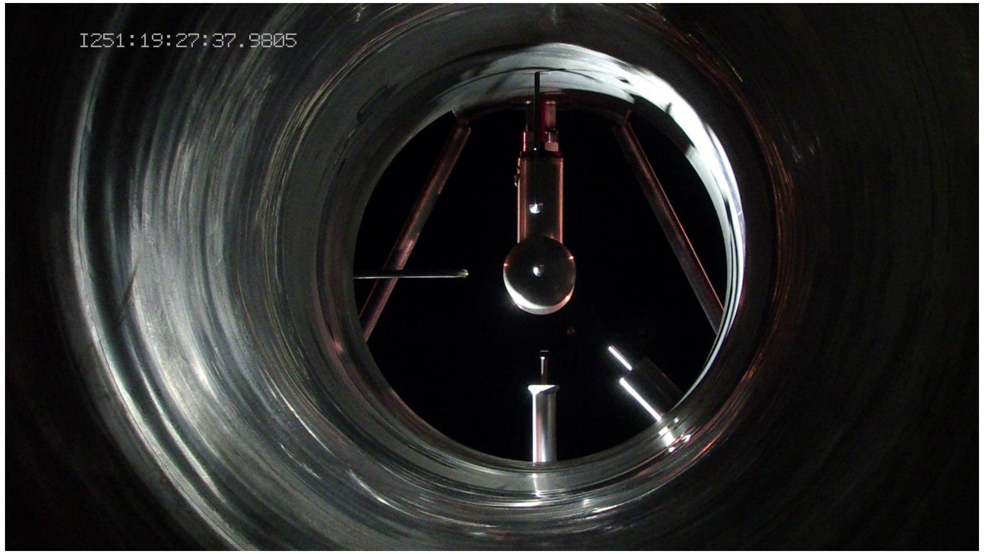
Bartkus et al. (2015, 2016, 2017)



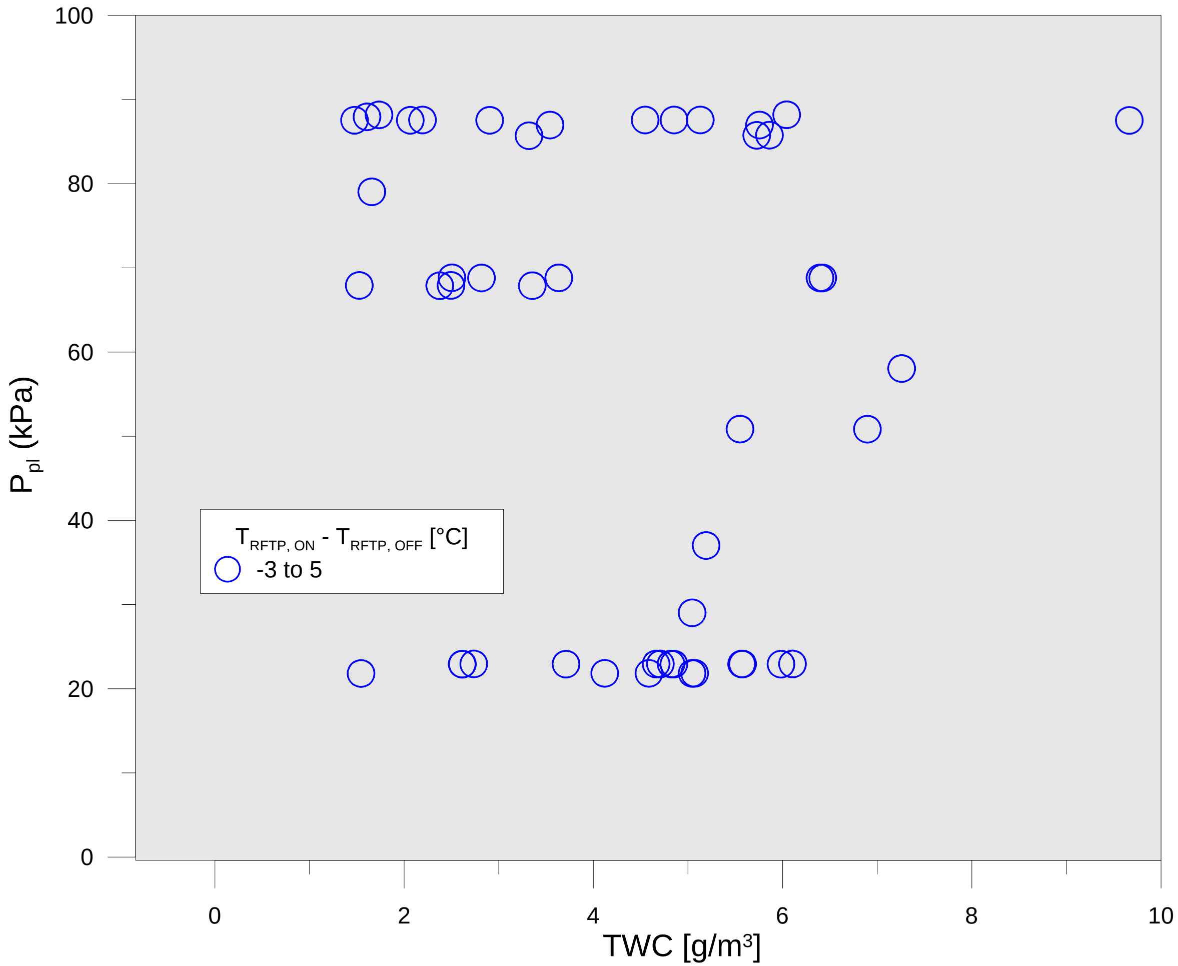
2017 Cloud Calibration Test Campaign

- **Test objectives**
  - Expand facility and measurement capabilities
  - Validate models
- **223 Test runs (conducted over 13 days)**
- **12 parameters can be varied:**

  P, V, Tair, Twater, RH, MVD, TWC, Water Type, Nozzle Pattern…
- **Data reduction**
  - Discard any unsteady or fluctuating signals or signals that did not reach equilibrium during cloud spraying.
  - average variables before and during spray
  - Determine delta Temperatures and humidity
- **Selection of variable sweeps (e.g. Total Water Content)**



Tests



100
80
60
40
20
0
P_{pl} (kPa)
0
2
4
6
8
10
TWC [g/m³]
$T_{RFTP, ON}$ - $T_{RFTP, OFF}$ [°C]
-3 to 5

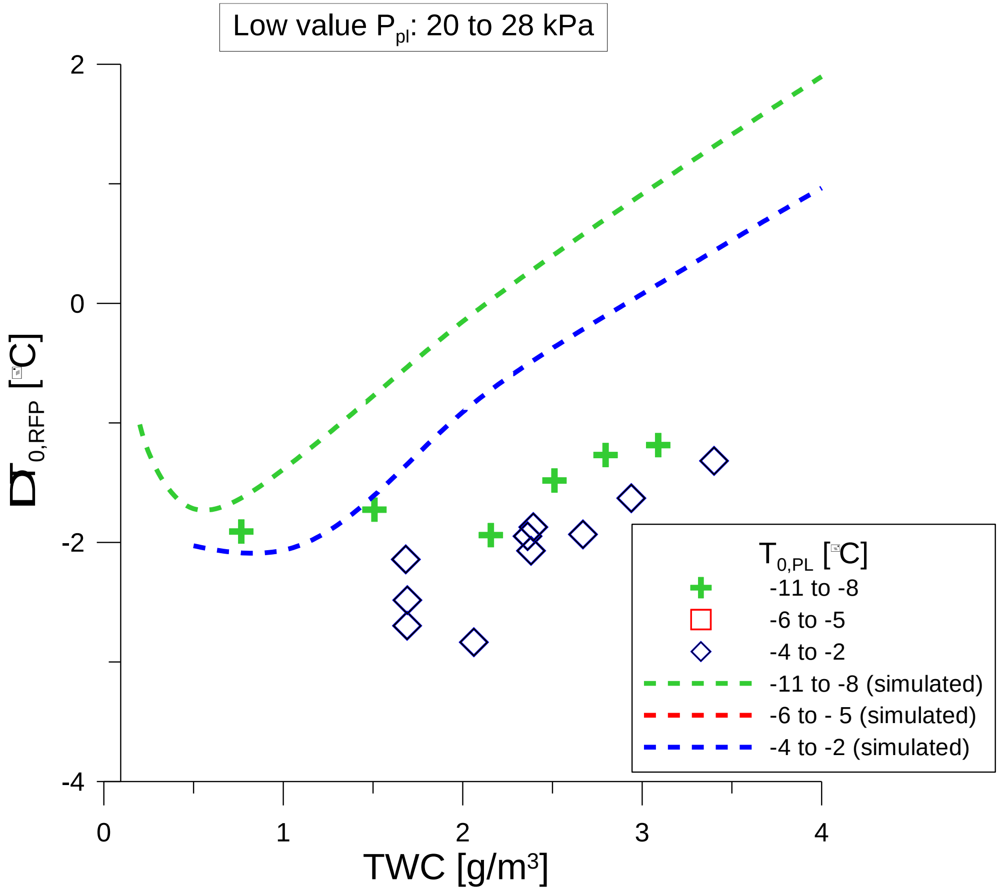
TWC sweeps

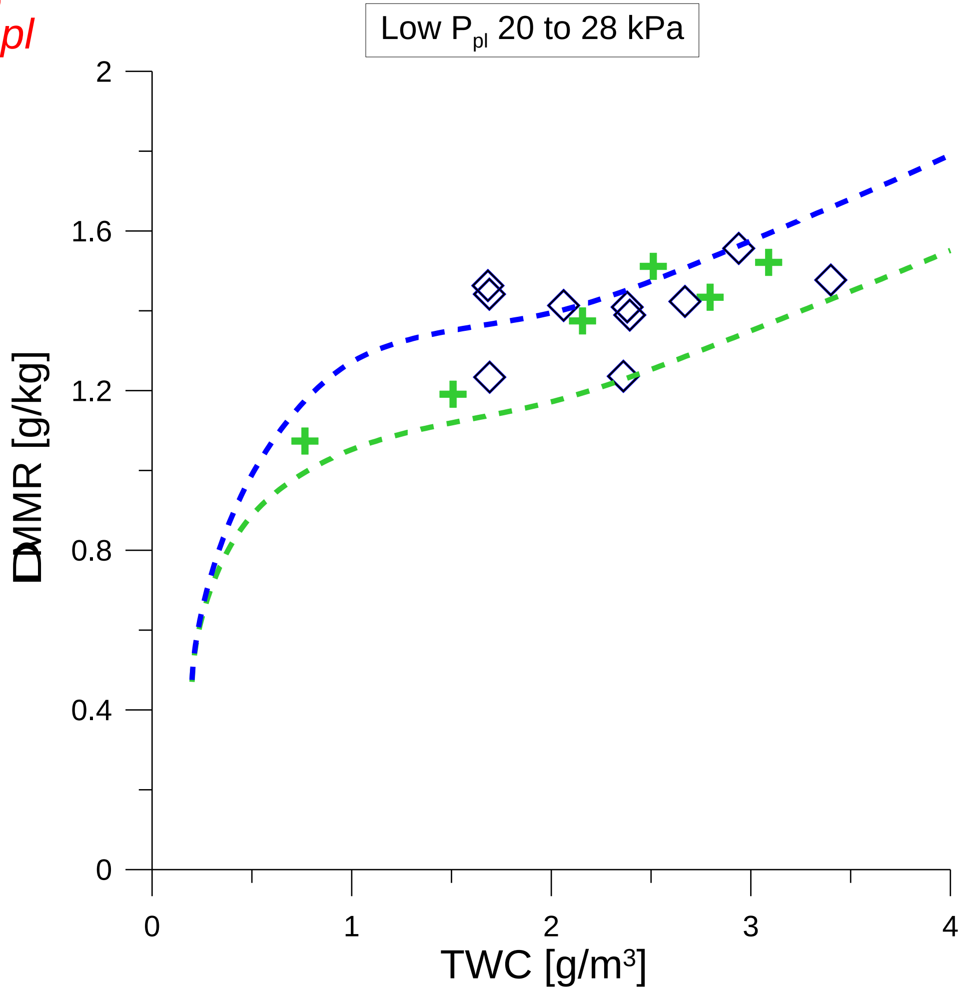
Plenum Pressure (P_{pl}) [kPa (Pisa)]	Plenum Temp. (T_{pl}) [°C]	Parameter in plots	Particle MVD [µm]	Mach	Tw [°C (°F)]	City/DI water	RH %
low: 20 to 28 (2.9 to 3)	low, mid, high*	Temp	15 - 20	0.44	7.2 (45)	City	45
mid: 62 to 70 (9 to 10.2)	low, mid, high*	Temp	15 - 20	0.22	82 (180)	DI	45
high: 90 to 97 (13 to 14)	low, mid, high*	Temp	15 - 20	.13 - .22	82 (180)	DI	45

Results

Negative Changes in Total temperature

Low P_{pl}

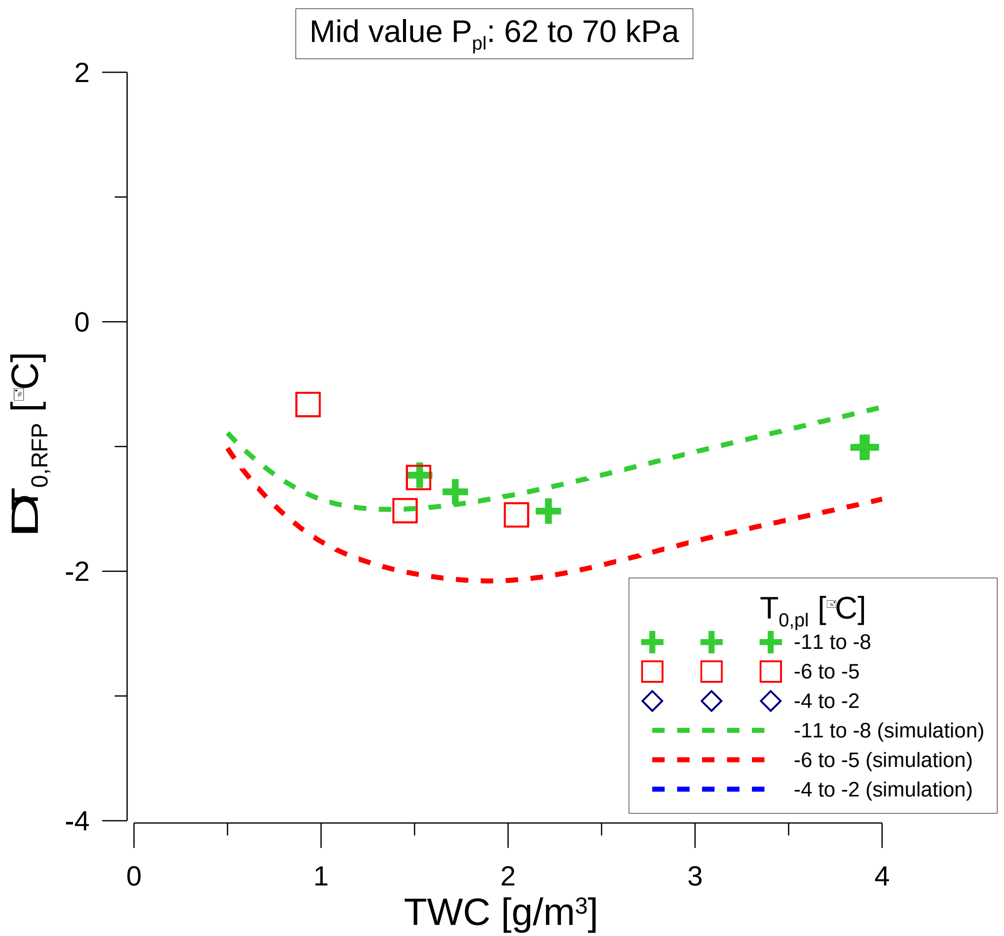


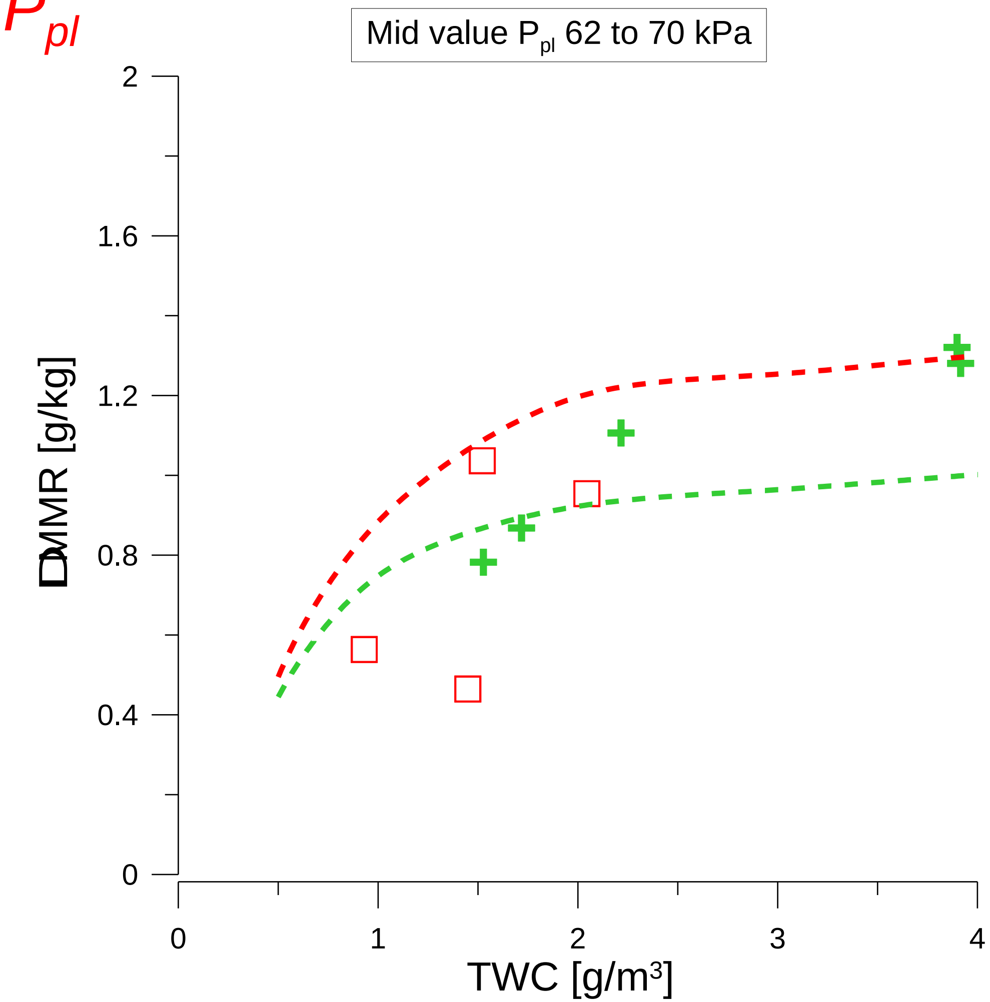


Results

Negative Changes in Total temperature

Mid P_{pl}

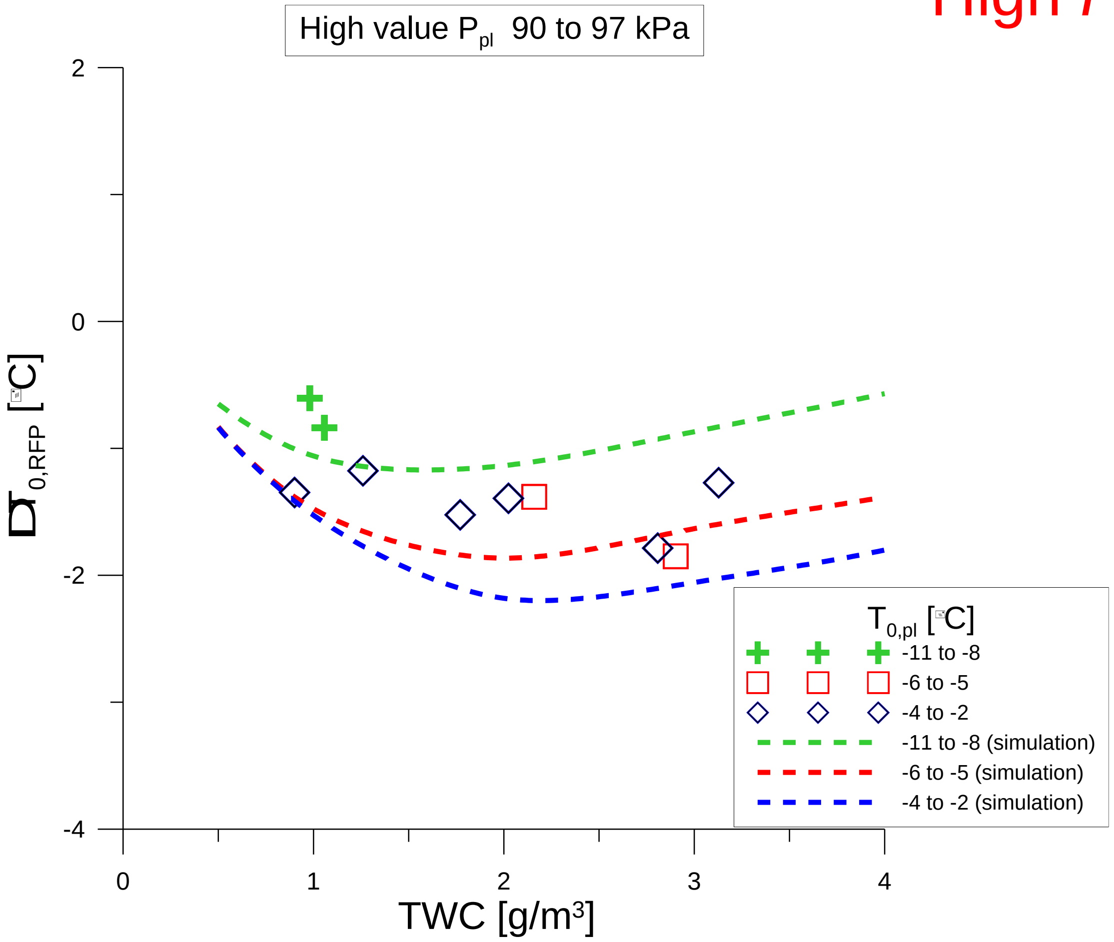


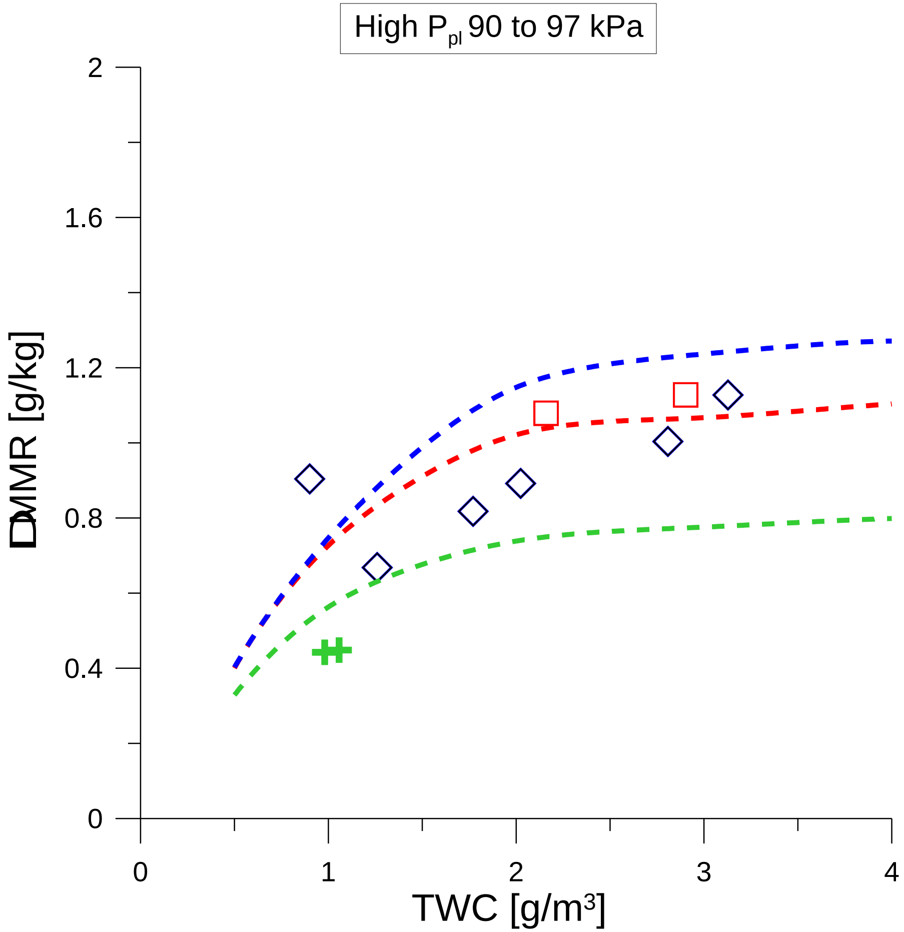


Results

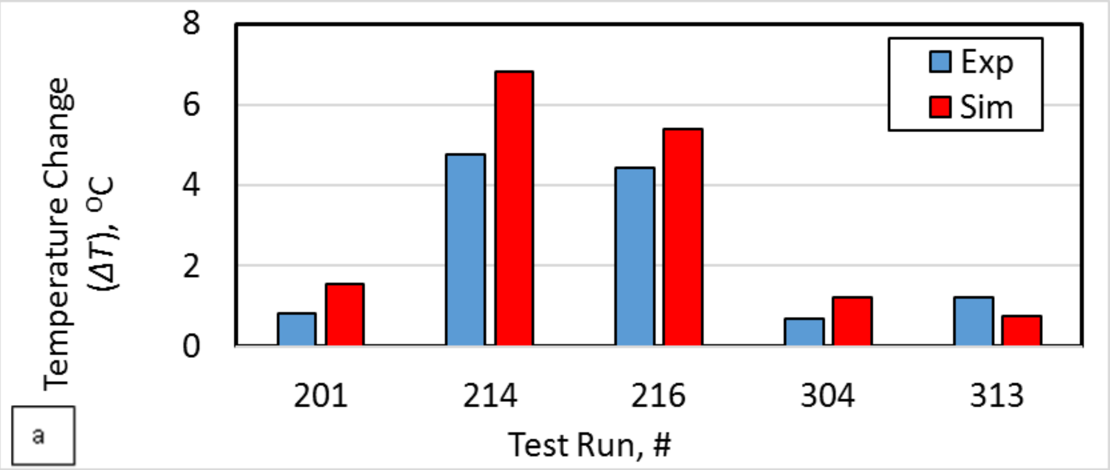
Negative Changes in Total temperature

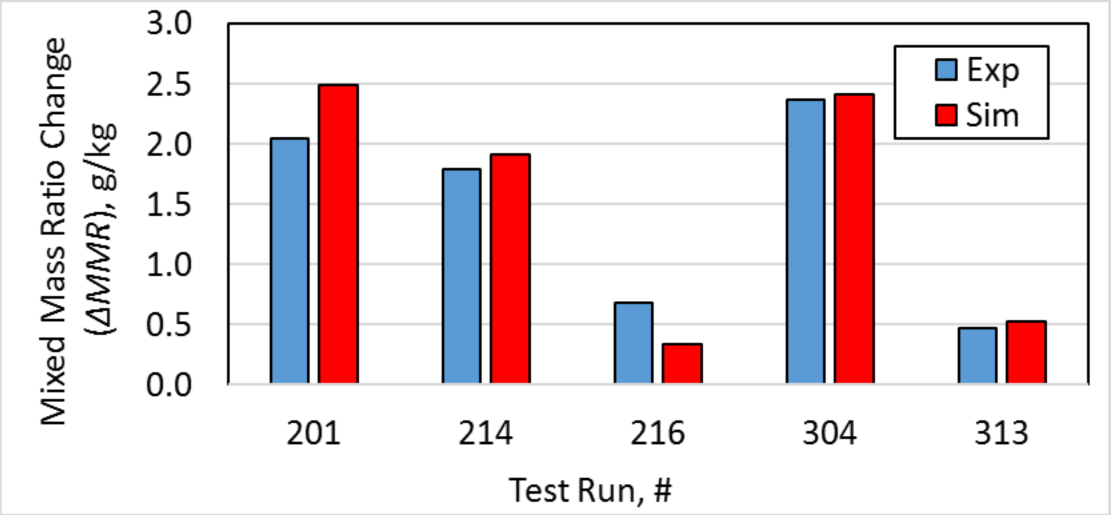
High P_{pl}





Cases with Positive increase in temperature





Test Run	T_{PL} (total)	P_{PL} (total)	RH_{PL} (Total)	Exit Air Velocity	Target TWC	Approx Initial MVD	Water Type	Initial Water Temp
#	[°C]	[kPa]	[%]	[m/s]	[g/m³]	[µm]	[City/DI]	[°C]
201	-3.1	22.5	45	144	6.52	33	City	8
214	-23.7	21.5	45	101	9.26	33	City	8
216	-35.7	23.9	45	128	4.70	41	City	8
304	-3.2	22.5	45	142	6.39	45	City	8
313	-15.7	86.6	45	115	6.45	24	City	8

Conclusions

• A Rearward Facing Probe is being developed in-house to measure local total temperature and humidity during atmospheric icing flow conditions.

• The thermal model showed that the large temperature differential between the injected droplet and the atmospheric flow produced competing evaporative and convective heat transfer effects.

Results:

• Small total temperature drops in the range of 0.6 to 2.8 ^{0}C and up to 1.5 g/kg of water vapor rise through the interaction.

• The largest changes in total temperature and humidity generally occurred at plenum conditions of low pressure and high temperature, and under glaciated cloud conditions.

• The least effects in total temperature were found at large *TWC* and low temperatures.

• Under certain high *TWC* conditions and glaciated , the interaction with the cloud produced a warming of the airflow.

• The thermal model in terms of evaporative and convecting heat transfer mechanisms helped in interpreting these trends.