DEVELOPMENT OF A COUPLED AIR AND PARTICLE THERMAL MODEL FOR ENGINE ICING TEST FACILITIES

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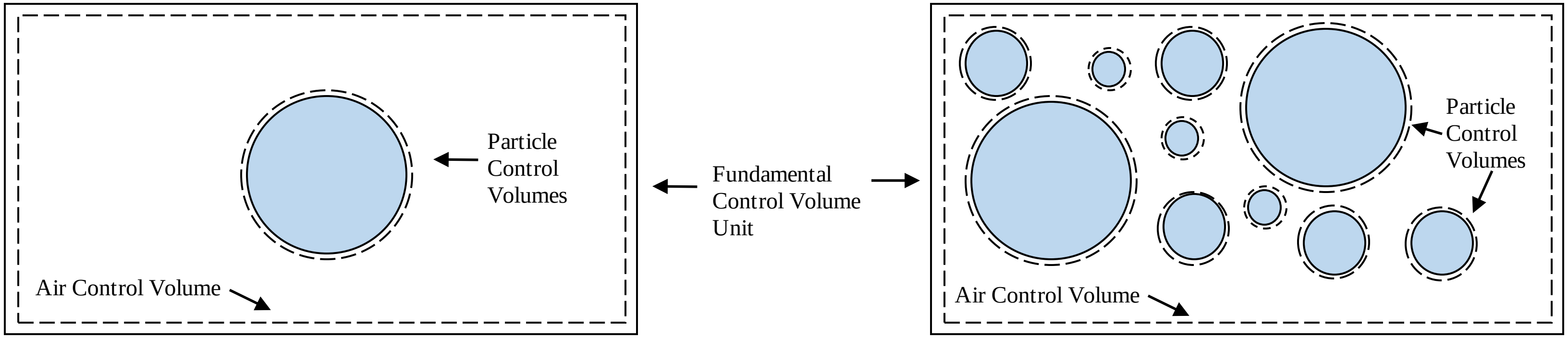
Introduction
Icing Observations

- Many engine power-loss events reported since the 1990's
- Mason et al.[1] hypothesized how power-loss events can result from ice crystals entering the engine core
- Ingestion of ice into engine is studied
- NASA conducted tests at NRC's RATFac
- Observed environmental conditions changed with cloud activation
  - Air temperature change
  - Air humidity change
  - Particle water content change
- Hypothesis : Thermal interaction between air and cloud particles

[1] Mason, J., Strap, J., and Chow, P., "The Ice particle Threat to Engines in Flight," presented at 44th AIAA Aerospace Sciences Meeting and Exhibit 2006, USA, January 9-12, doi: 10.2514/6.2006-206

Thermal Model General Description

- Model couples air and cloud particle conservation equations
  - Mass, energy and momentum
- Simulates icing tunnel (applicable to engines too)
- Ice, water, and humid air mass broken into fundamental CV units
  - Uniform particle size (MVD representation)
  - Full particle size distribution



Single particle depiction (uniform particle size cloud)

Full particle size distribution particle depiction (multiple particle size cloud)

Assumptions

- Air and water vapor are treated as ideal gases
- Air is continually well mixed
- No supersaturation
- 1-D air and particle flow
- Dilute system (no particle interaction)
- Particles are spherical
- Discrete particle size distribution (bins)
- Uniform temperature within the particle
- Supercooling can occur
- Mixed phase particles are not spatially resolved
- Phase change occurs at particle surface at particle temperature
- Adiabatic tunnel walls
- The flow of particles and air is a continuous stream
- The fundamental CV is adiabatic and mass is conserved
  - Provisions for heat and mass transfer added using source terms

Particle Conservation of Energy
Single Particle Formulation (1/2)

- Change in the particle's enthalpy, is due to the convective heat transfer and latent energy exchange due to mass transfer

$$\frac{\partial H_p}{\partial t} = q_{conv} + q_{latent}$$

- Rate of mass change with a water surface is proportional to the difference in vapor pressure between the particle surface and the ambient air

Ice: $\rho_p C_p \frac{\pi d^3}{6} \frac{\partial T_p}{\partial t} = \pi d^2 h\left(T_{air} - T_p\right) + \pi d^2 h_m \rho_{air} L_{subl}\left(\omega_{air} - \omega_p\right)$

Mix: $\rho_p L_{melt} \frac{\pi d^3}{6} \frac{\partial \eta_p}{\partial t} = \pi d^2 h\left(T_{air} - T_p\right) + \pi d^2 h_m \rho_{air} L_{subl/evap}\left(\omega_{air} - \omega_p\right)$

Water: $\rho_p C_p \frac{\pi d^3}{6} \frac{\partial T_p}{\partial t} = \pi d^2 h\left(T_{air} - T_p\right) + \pi d^2 h_m \rho_{air} L_{evap}\left(\omega_{air} - \omega_p\right)$

Particle Conservation of Energy
Single Particle Formulation (2/2)

- Empirical heat and mass transfer expressions for flow over a sphere[2]
  - $Nu = \frac{hd}{k_{air}} = 2 + 0.6 Re^{1/2} Pr^{1/3}$
  - $Sh = \frac{h_m d}{D_{ab}} = 2 + 0.6 Re^{1/2} Sc^{1/3}$
  - $Re = \frac{\rho_{air} |v_{air} - v_p| d}{\mu_{air}}$
  - $Pr = \frac{C_{air} \mu_{air}}{k_{air}}$
  - $Sc = \frac{\mu_{air}}{\rho_{air} D_{ab}}$
  - $\omega_{air} = \frac{MW_{water}}{MW_{air}} \frac{P_{wv,air}}{P_{air}}$
  - $\omega_{surf} = \frac{MW_{water}}{MW_{air}} \frac{P_{wv,surf}}{P_{air}}$

[2] Incropera, F., and DeWitt, D., "Fundamentals of Heat and Mass Transfer, Fourth Edition," (New York, John Wiley & Sons, 1996) ISBN: 0471304603.

Air Conservation of Energy
Single Particle Formulation

- Change in the air enthalpy is due to the convective heat transfer and the sensible energy change of the water vapor mass that has changed phase
  - $\frac{\partial H_{air}}{\partial t} = q_{conv} + q_{wv,sens}$
- $q_{wv,sens}$ is thermal mixing
  - $m_{air} C_{air} \frac{\partial T_{air}}{\partial t} = \pi d^2 h\left(T_p - T_{air}\right) + \frac{\partial m_{wv}}{\partial t} \int_{T_{air}}^{T_p} C_{wv}\, \partial T$
- m_{wv} can be mass from evaporation or mass to condense

Conservation of Mass
Single Particle Formulation

- Change in particle mass due to vapor phase change
  - $\frac{\partial m_p}{\partial t} = \rho_p \frac{\partial}{\partial t}\left(\frac{\pi d^3}{6}\right) = \pi d^2 h_m \rho_{air}(\omega_{air} - \omega_p)$
- Change in air mass is opposite the change in particle mass
  - $\frac{\partial m_{air}}{\partial t} = -\frac{\partial m_p}{\partial t} = \pi d^2 h_m \rho_{air}(\omega_p - \omega_{air})$

Conservation of Energy
Particle Distribution Formulation

- MVD vs particle distribution
  - Smaller particles have greater SA/Vol ratio → faster transfer response
  - Cumulative differences will add up to a different final result
  - Fraction of the total water mass calculated for every particle size bin

- An energy balance equation for every particle size *i*
  - $\rho_{p,i} C_{p,i} \frac{\pi d_i^3}{6} \frac{\partial T_{p,i}}{\partial t} = \pi d_i^2 h_i \left(T_{air} - T_{p,i}\right) + \pi d_i^2 h_{m,i} \rho_{air} L_i (\omega_{air} - \omega_{p,i})$

- One air energy equation contains the sum of all the particle heat transfers and vapor sensible energy transfers.
  - $m_{air} C_{air} \frac{\partial T_{air}}{\partial t} = \sum_{i=1}^{n} \left[\pi d_i^2 h_i \left(T_{p,i} - T_{air}\right) + \frac{\partial m_{wv,i}}{\partial t} \int_{T_{air}}^{T_{p,i}} C_{wv,i} \, \partial T \right] (\#_i)$
    - n = number of particle size bins
    - $\#_i$ = number of particles in the i^{th} bin

Conservation of Mass
Particle Distribution Formulation

- A mass balance equation for every particle size *i*
  - $\frac{\partial m_{p,i}}{\partial t} = \pi d_i^2 h_{m,i} \rho_{air} \left(\omega_{air} - \omega_{p,i} \right)$

- One air mass equation contains the sum of all the particle mass transfers.
  - $\frac{\partial m_{air}}{\partial t} = -\sum_{i=1}^{n} \left[\frac{\partial m_{p,i}}{\partial t} \right] (\#_i)$

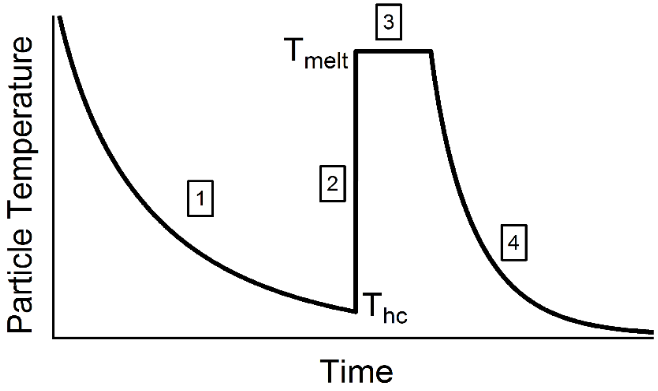
Conservation of Momentum

- Conservation of momentum equation is solved in reference to particle
- $F = F_{drag} + F_g = m_p a = \rho_p \frac{\pi d^3}{6} \frac{\partial v_p}{\partial t}$
  - $F_g = 0$
  - $F_{drag} = \frac{1}{2} \rho_{air} U^2 A C_D$
  - $U = v_{air} - v_p$
  - $A = \pi d^2$
  - $C_D = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1+\left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263,000}\right)^{-7.94}}{1+\left(\frac{Re}{263,000}\right)^{-8.00}} + \frac{Re^{0.80}}{461,000}$ (Morrison correlation[3])
- $\frac{\partial v_p}{\partial t} = \frac{3}{4} \frac{\rho_{air} C_D \left(v_{air} - v_p\right)^2}{\rho_p d}$

[3]Morrison, F., "An Introduction to Fluid Mechanics," (New York, Cambridge University Press, 2013) pg. 625, ISBN: 1107003539.

Supercooled Freezing Formulation

- Four stages in supercooled freezing
  1. Sensible liquid cooling (below 273.15K)
  2. Latent heat release
  3. Latent freezing (at 273.15K)
  4. Sensible ice cooling



- Homogeneous crystallization temperature as a function of diameter[4]
  - $T_{hc} = 7.2015 \ln(d) + 214.64$

- Expressions to determine melt fraction after latent heat release
  - $H_{sens,super} = m_p \int_{T_{hc}}^{273.15} C_p(T)dT$
  - $\eta_p = 1 - \frac{m_p L_{melt} - H_{sens,super}}{m_p L_{melt}}$

[4]Heverly, J., "Supercooling and Crystallization," *Transactions of American Geophysical Union* 30(2): 205-10, 1949.

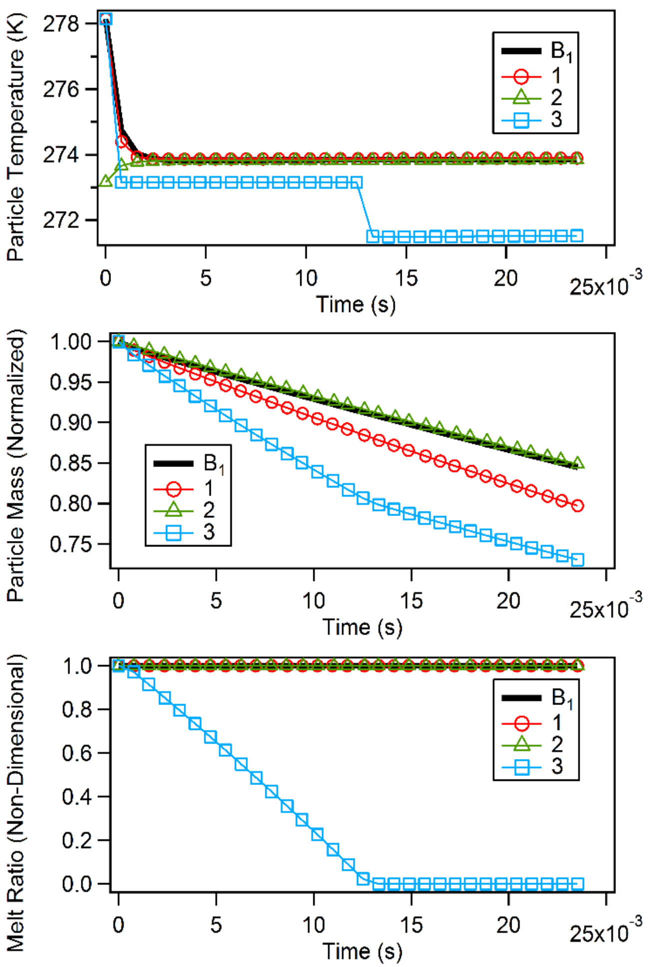
Algorithm

- Written in MATLAB version R2014a
- Solves conservation equations using built-in ODE45 solver
- Relative and absolute convergence tolerance of 10^{-12}
- Mass transferred between the air and particle(s) balanced to 10^{-15}
- Energy transferred between the air and particle(s) balanced to 10^{-4}
  - Model accuracy dependent on accuracy of property values (C_p, L_{heat}, etc.)

Parametric Analysis
Baseline 1 Tests

	Units	Baseline 1
Particle Diameter	µm	10
LWC	g/m^3	1
Pressure	Pa	88,000
Relative Humidity	%	50
Air Temperature	K	278.15
Particle Temperature	K	278.15
Slip Velocity	m/s	5

Test #	Parameter Changed	Units	Value
Baseline 1			
1	Slip Velocity	m/s	25
2	Particle Temperature	K	273.15
3	Pressure	Pa	28,000

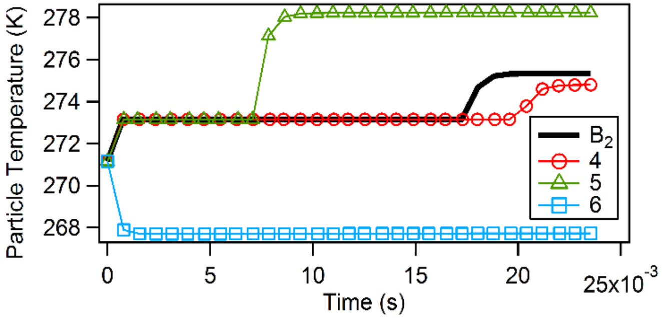


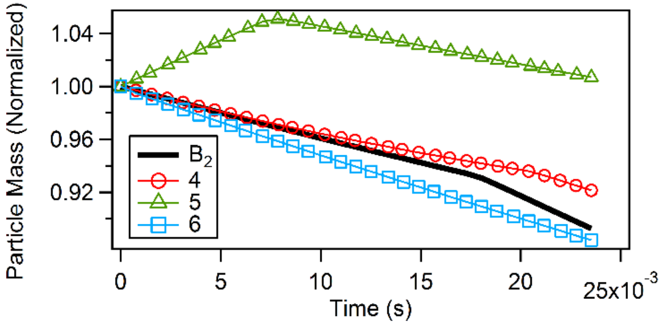
Takeaway: Wet-bulb temperature determines state of particle

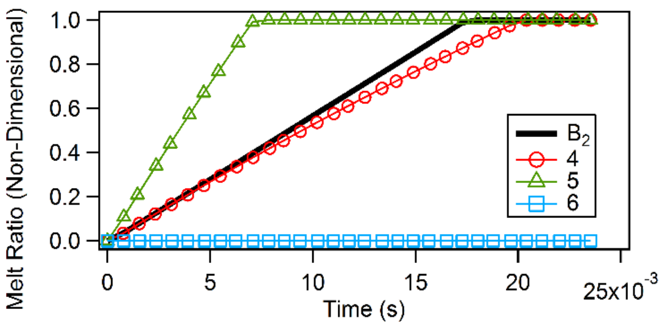
Parametric Analysis
Baseline 2 Tests

	Units	Baseline 2
Particle Diameter	µm	10
IWC	g/m^3	1
Pressure	Pa	88,000
Relative Humidity	%	50
Air Temperature	K	280.15
Particle Temperature	K	271.15
Slip Velocity	m/s	5

Test #	Parameter Changed	Units	Value
Baseline 2			
4	IWC	g/m^3	5
5	Relative Humidity	%	80
6	Air Temperature	K	271.15



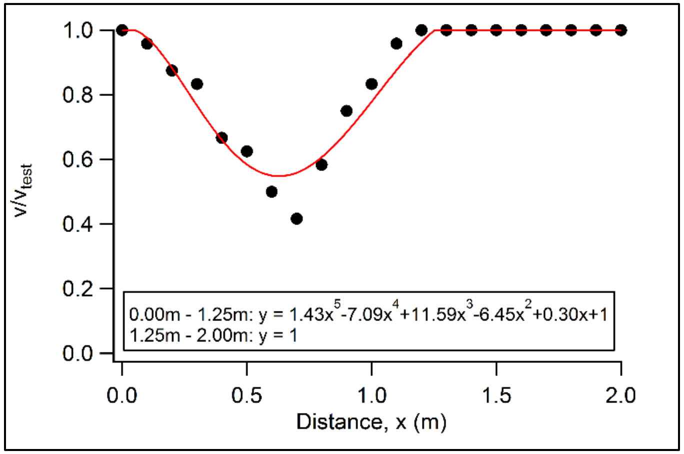




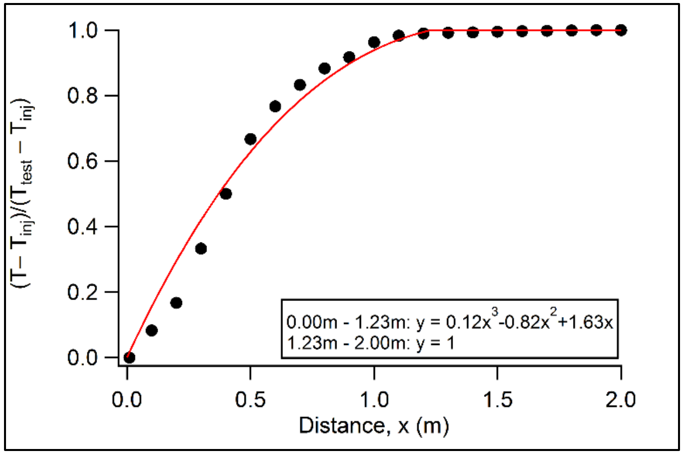
Takeaway: Air thermal mass >> Particle thermal mass

Thermal Model – RATFac Modifications
Air Heat, Air Velocity, Air Vapor Mass Sources

- Air velocity, air temperature, and vapor content vary from injection to test section at RATFac (no icing cloud)
- CFD model previously written to approximate v_{air} and T_{air}
- Centerline values normalized
- Water vapor profile analogous to normalized air temperature profile
- Approximate changing values as sources in expressions (no cloud)
  - Valid for tests Mach ~ 0.2 and P_{total} ~ 44000 Pa at test section



Normalized air velocity at centerline (without an icing cloud)



Normalized air temperature at centerline (without an icing cloud)

Model – Experiment Comparison

	Units	Scan 877	Scan 983	Scan 1003
$T_{air,inj}$	K	262.0	256.1	256.9
$T_{air,target}$	K	288.4	278.0	277.9
SH_{inj} (RH_{inj})	$g_{vapor}/kg_{dry\ air}$ (%)	0.07 (2)	0.07 (5)	0.07 (4)
SH_{target} (RH_{target})	$g_{vapor}/kg_{dry\ air}$ (%)	4.07 (16.1)	2.88 (35.4)	3.81 (46.5)
$GWC_{inj/target}$	g/m^3	2.1	2.4	3.0
$LWC_{inj/target}$	g/m^3	1.0	0	1.9
$IWC_{inj/target}$	g/m^3	0	8.4	8.6
$\eta_{inj/target}$	-	1.0	0.0	0.18
P	Pa	42806	66478	65934
$v_{air,inj/target}$	m/s	86.8	85.7	84.1
$T_{water,inj}$	K	278.15	-	278.15
$T_{ice,inj}$	K	-	256.15	256.15
$MVD_{water,inj}$	µm	40.0	-	40.0
$MVD_{ice,inj}$	µm	-	45.5	45.5

	Units	Scan 877	Scan 983	Scan 1003
$\Delta T_{air,\ exp}$	K	-2.6	-2.9	-4.4
$\Delta T_{air,\ sim}$	K	-0.54	-0.75	-0.88
ΔGWC_{exp}	g/m^3	0.5	1.0	1.2
ΔGWC_{sim}	g/m^3	0.13	0.16	0.21
ΔLWC_{exp}	g/m^3	-0.5	0.5	0.2
ΔLWC_{sim}	g/m^3	-0.13	0.0	-0.09
ΔIWC_{exp}	g/m^3	0.0	-1.5	-1.4
ΔIWC_{sim}	g/m^3	0.0	-0.16	-.12
$\Delta\eta_{exp}$	-	0.00	0.07	0.05
$\Delta\eta_{sim}$	-	0.00	0.00	-0.004

- Conditions
  - Scan 887: Water sprayed into low P, low RH, very warm air
  - Scan 983: Ice sprayed into medium P, medium RH, warm air
  - Scan 1003: Water & Ice sprayed into medium P, medium RH, warm air

Takeaway: Model accounts for ~20% of experimentally observed changes

Sources for Model – Experiment Discrepancy

- Experimentally observed water/ice film on tunnel walls
  - Increased residence time for evaporation
- Poor approximation for the vapor mass source term
- Non-spherical particles increase heat and mass transfer
- Turbulence at spray nozzle may enhance transfer
- Uncertainties with experimentally measured values
  - Independent corroborating measurements minimize this possibility

Conclusion

Thermal model that couples particle and air conservation equations

- Simulates:
  - All phase change types
  - Supercooled and normal freezing
  - Single particle and full particle distribution sprays (ice, water, combined)
  - Complicated icing tunnels with energy and mass sources
- Air temperature, pressure (air mass), and RH dominate → T_{wb}
- Model compared to experiments conducted at NRC
  - Simulated ~ 20% of the cloud and air changes observed experimentally
  - Reasons for discrepancy are offered
- Future work to determine sources for discrepancy
- Model can be modified to simulate other icing facilities (PSL)