A Thermal Analysis of a Hot-Wire Probe for Icing Applications

Peter Struk

NASA GRC

Dave Rigby

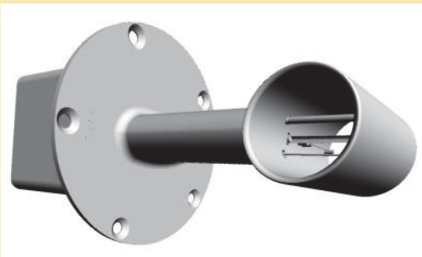
NASA GRC, Vantage

Krishna Venkataraman

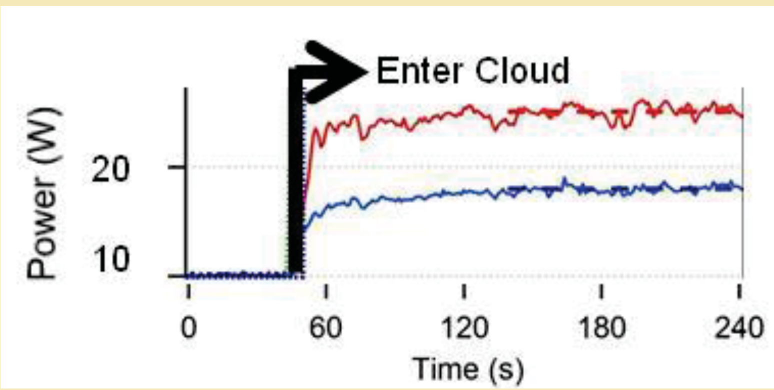
University of Texas, Austin

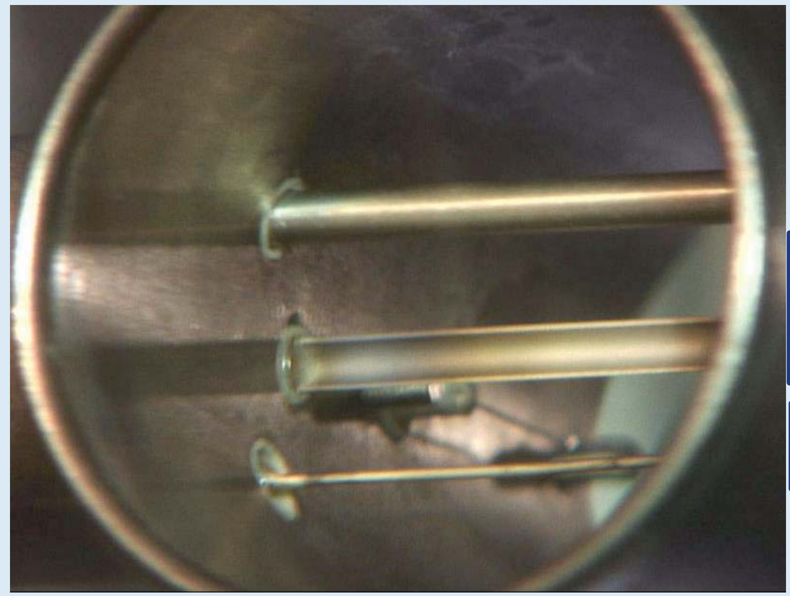
Motivation

- Further understand behavior of hot-wire measurements in icing conditions
- Newer applications in ice crystals and mixed phase



SEA Multi-Element Probe





083

Half-Pipe (HP)

021

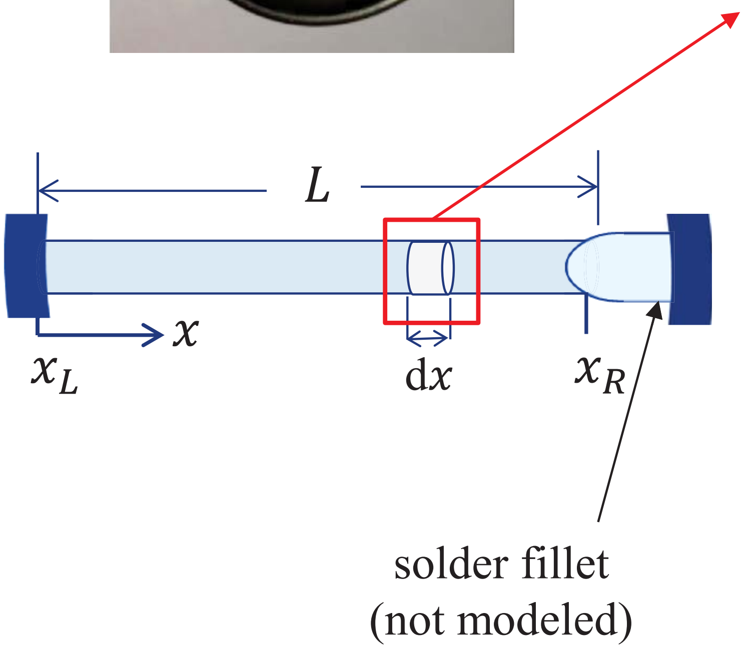
Video in IWC cloud

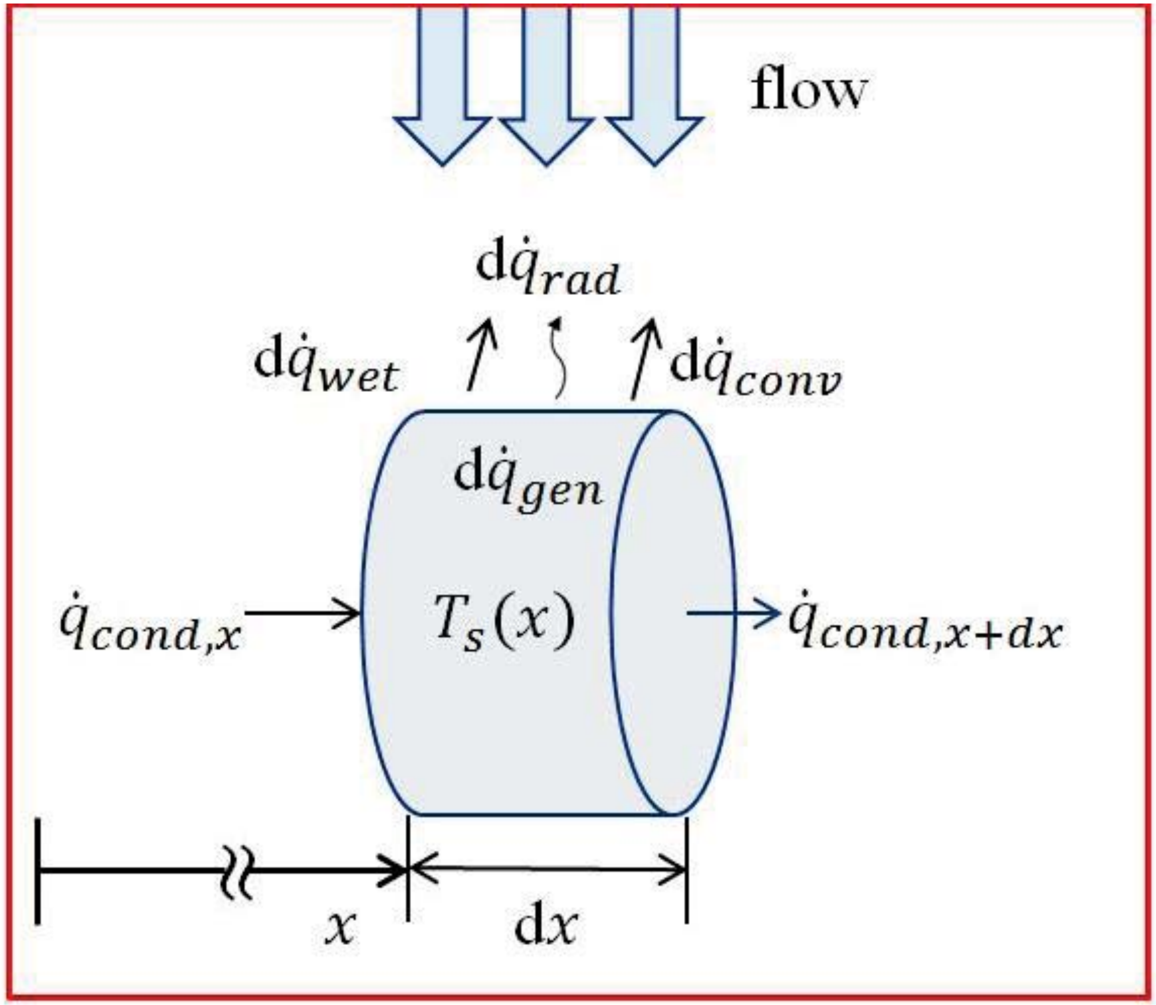
Particle impingement uniformity → Rigby et al. (Aviation 2014)
Temperature profile along wire → Thermal model (this paper)

Outline

- Describe Thermal Model
  - Governing equations
  - Model parameters
- Results (model vs. experiment)
  - Dry (air flow only, no water)
  - Wet (i.e. cloud on with LWC or IWC)
- Conclusions

Thermal Model Based on Energy Balance





$$d\dot{q}_{gen} = d\dot{q}_{conv} + d\dot{q}_{cond} + d\dot{q}_{rad} + d\dot{q}_{wet}$$

Governing Equation

$$\frac{d^2T_s}{dx^2} + \frac{1}{k}\frac{dk}{dT_s}\left[\frac{dT_s}{dx}\right]^2 - \frac{P}{d_o}\frac{k_a}{kA_C}Nu\left[T_s - T_{a,0}\right] - \frac{\varepsilon\sigma P}{kA_C}\left[T_s^4 - T_{sur}^4\right] + \frac{i^2\rho}{kA_C^2} - \frac{1}{kA_C}\frac{d\dot{q}_{wet}}{dx} = 0$$

Conduction | Convection | Radiation | Heat Generation | Heat Sink (Water / Ice)

2nd Order, Non-Linear ODE
solved using MATLAB routine *bvp4c*

Boundary Value Problem
need two boundary conditions

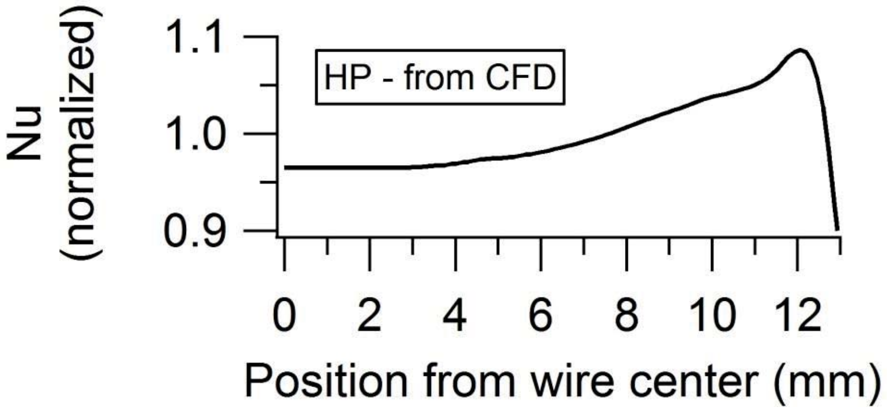
Model Parameters

- Boundary Conditions

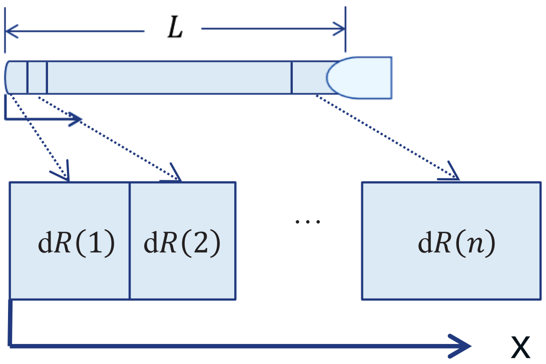
$$\left.\frac{dT}{dx}\right|_{xL} = 0$$

$$T\big|_{R} = 50°\text{C}$$

- Convection correlations
  - (1) Sparrow et. al - 2004
  - (2) Generated from CFD



- Probe operation
  - Maintains const. avg. temp (e.g. resistance) ~140 °C
  - Temp (Res) ↓, Power ↑



$$R = \sum_{j=1}^{n} dR(j)$$

Wire Power
$P = i^2 R$

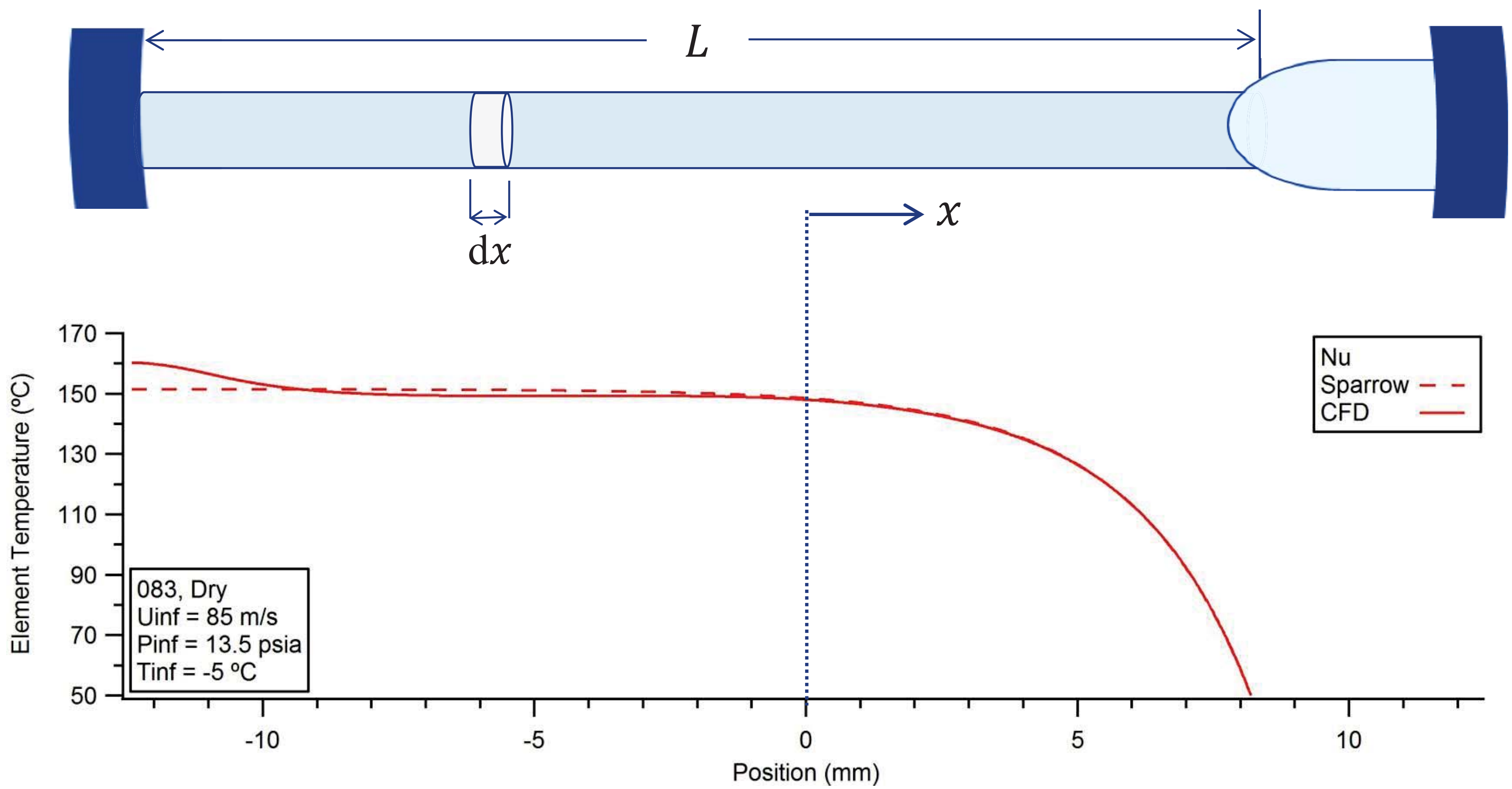
Results

- Experimental results from 2012 NRC RATFac Tests

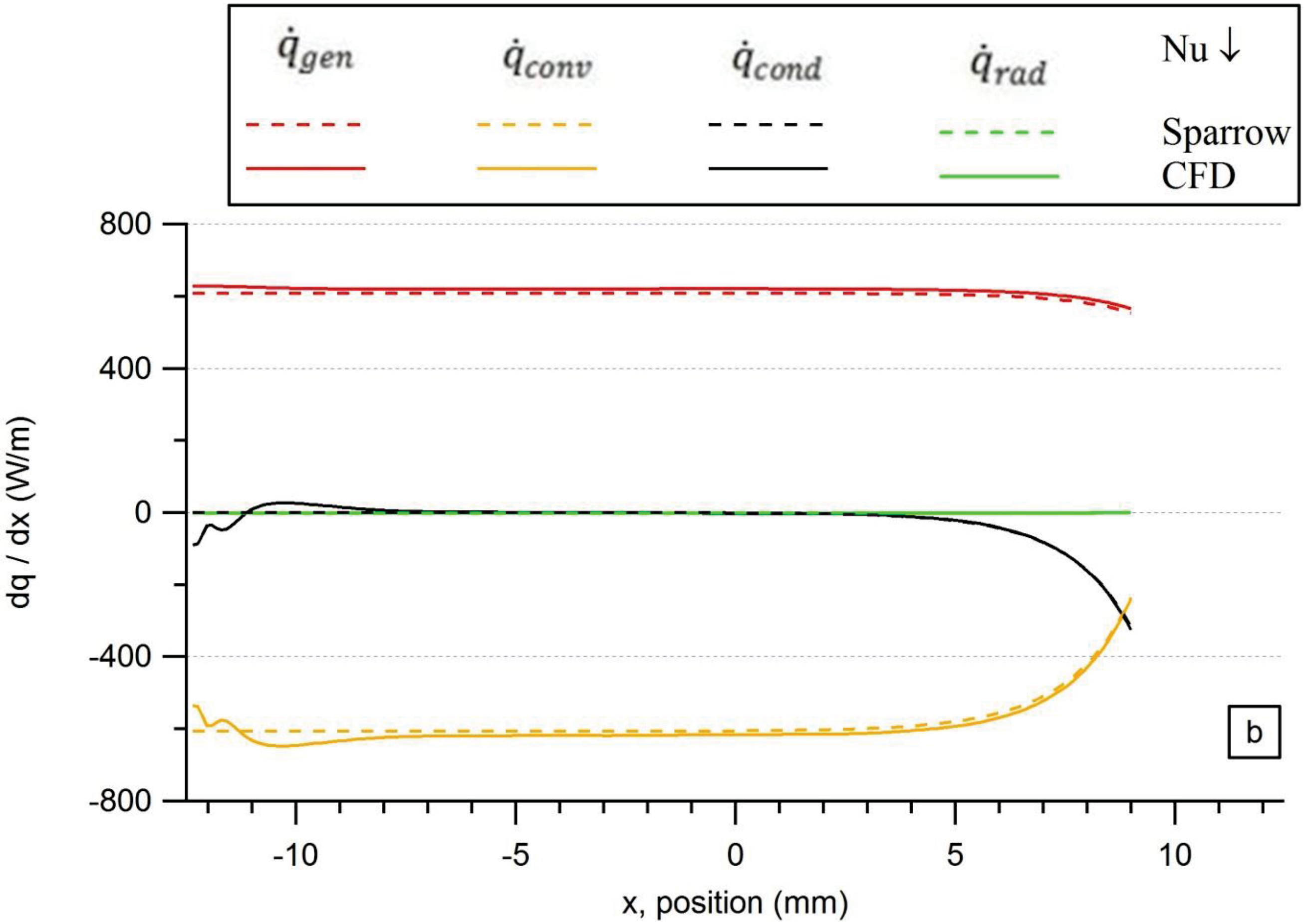
- Dry Conditions (P_0=13.5, 6.5 psia; U=85,100,135 m/s)
  - Temperature profiles
  - Total power (experiment vs. model)
    - Effect of heat-transfer coefficient

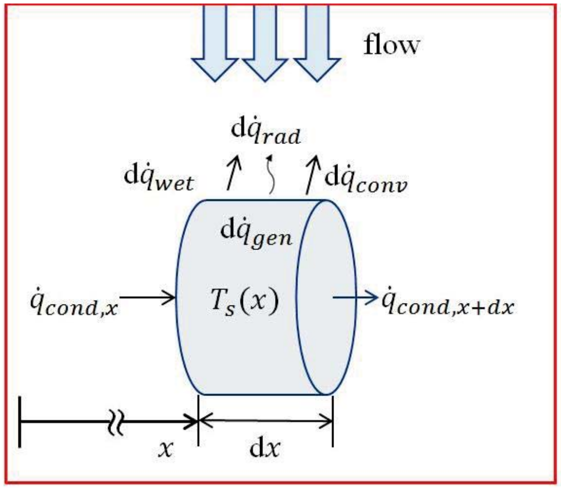
- Wet results (P_0 = 13.5 psia, U = 85 m/s)
  - LWC Sweep 0-3 g/m^3
  - IWC Sweep 0-10 g/m^3

Results: *Temperature Profiles – Dry*



dq/dx along Wire - Dry

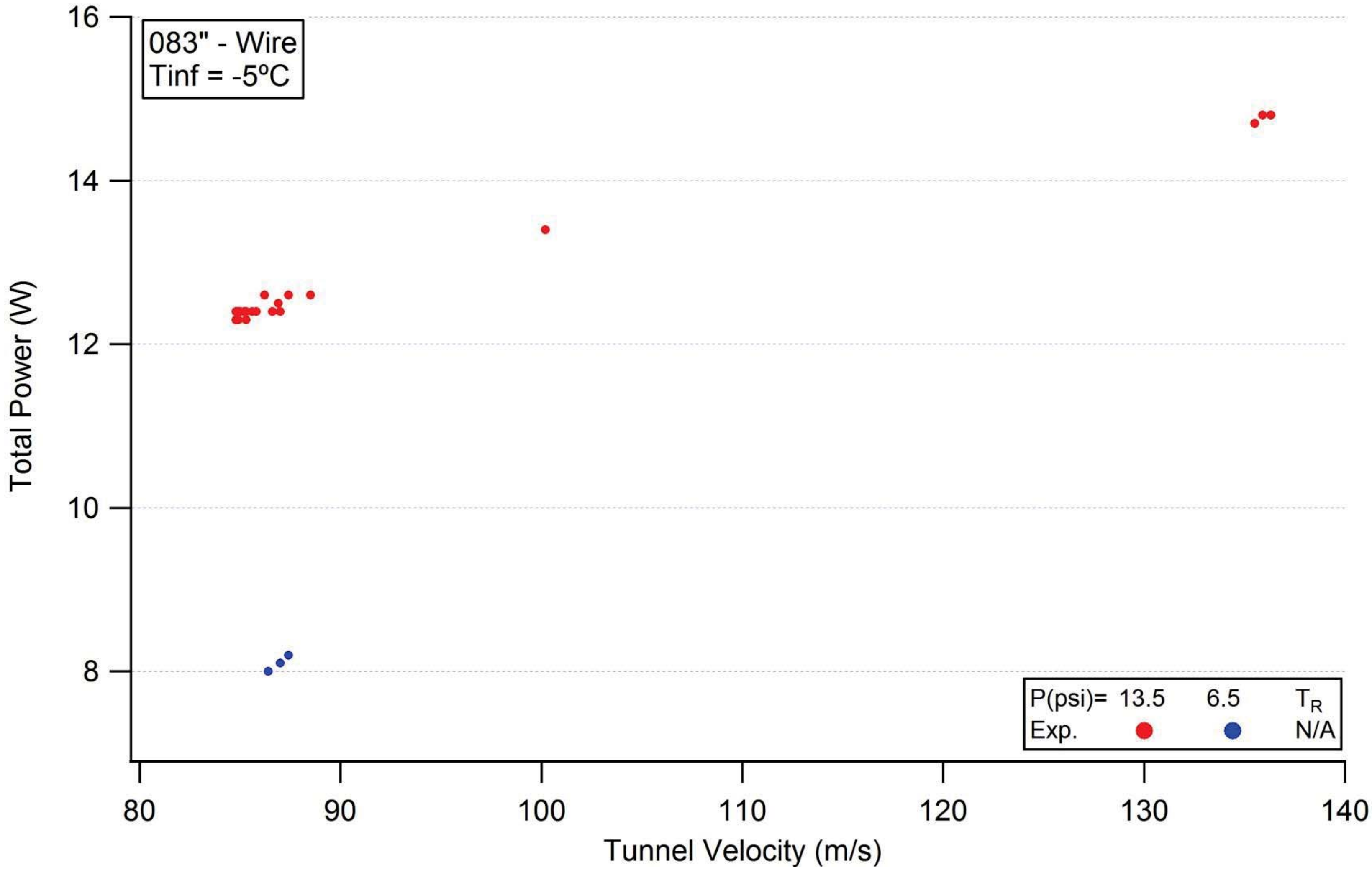




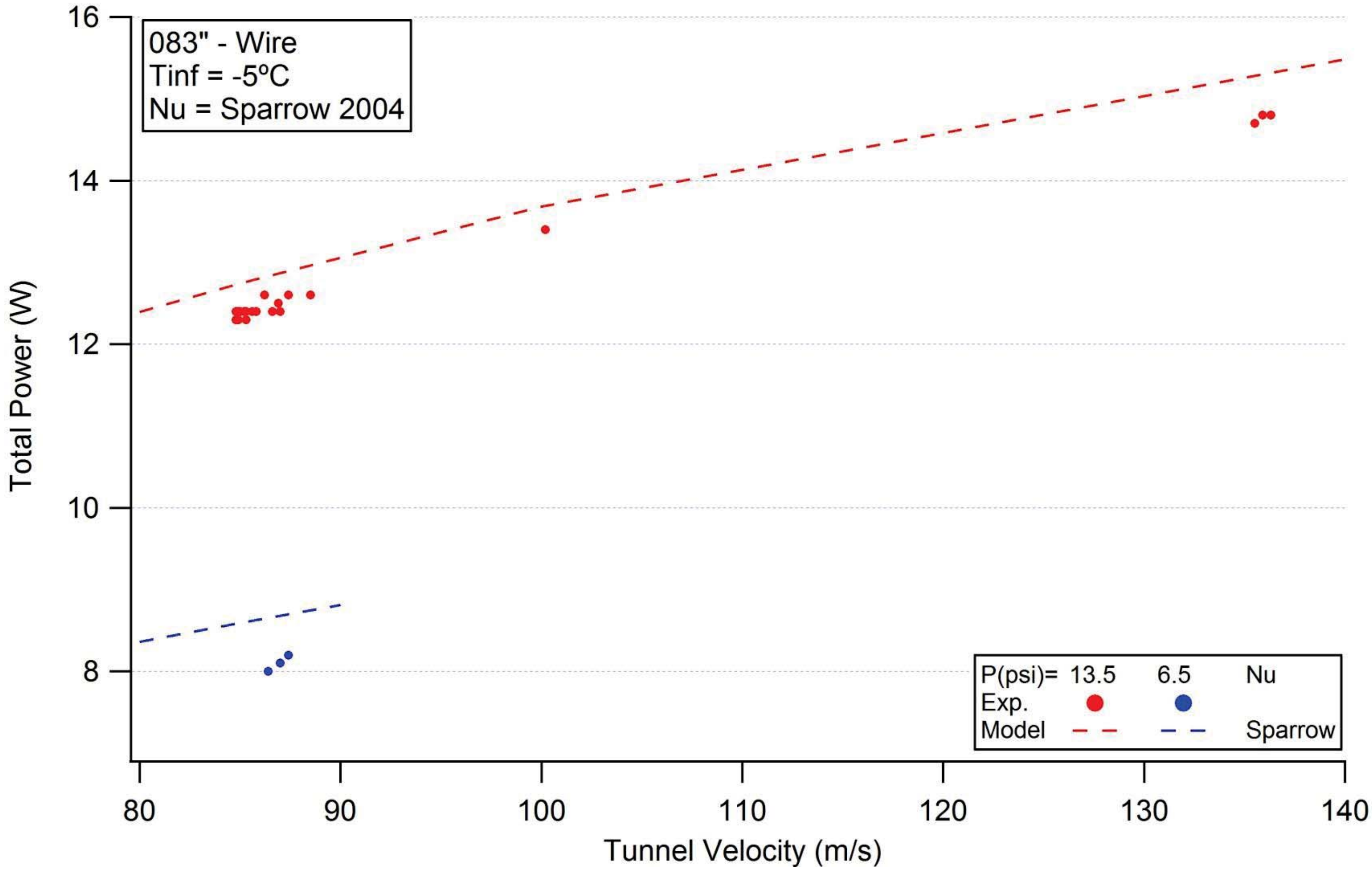
Integrated Values (Nu = Sparrow)

Term	Dry
$\dot{q}_{gen}$ (W)	12.743
$\dot{q}_{conv}$ (W)	-11.945
$\dot{q}_{cond}$ (W)	-0.766
$\dot{q}_{rad}$ (W)	-0.032
$\dot{q}_{wet}$ (W)	0.000
Sum	0.000

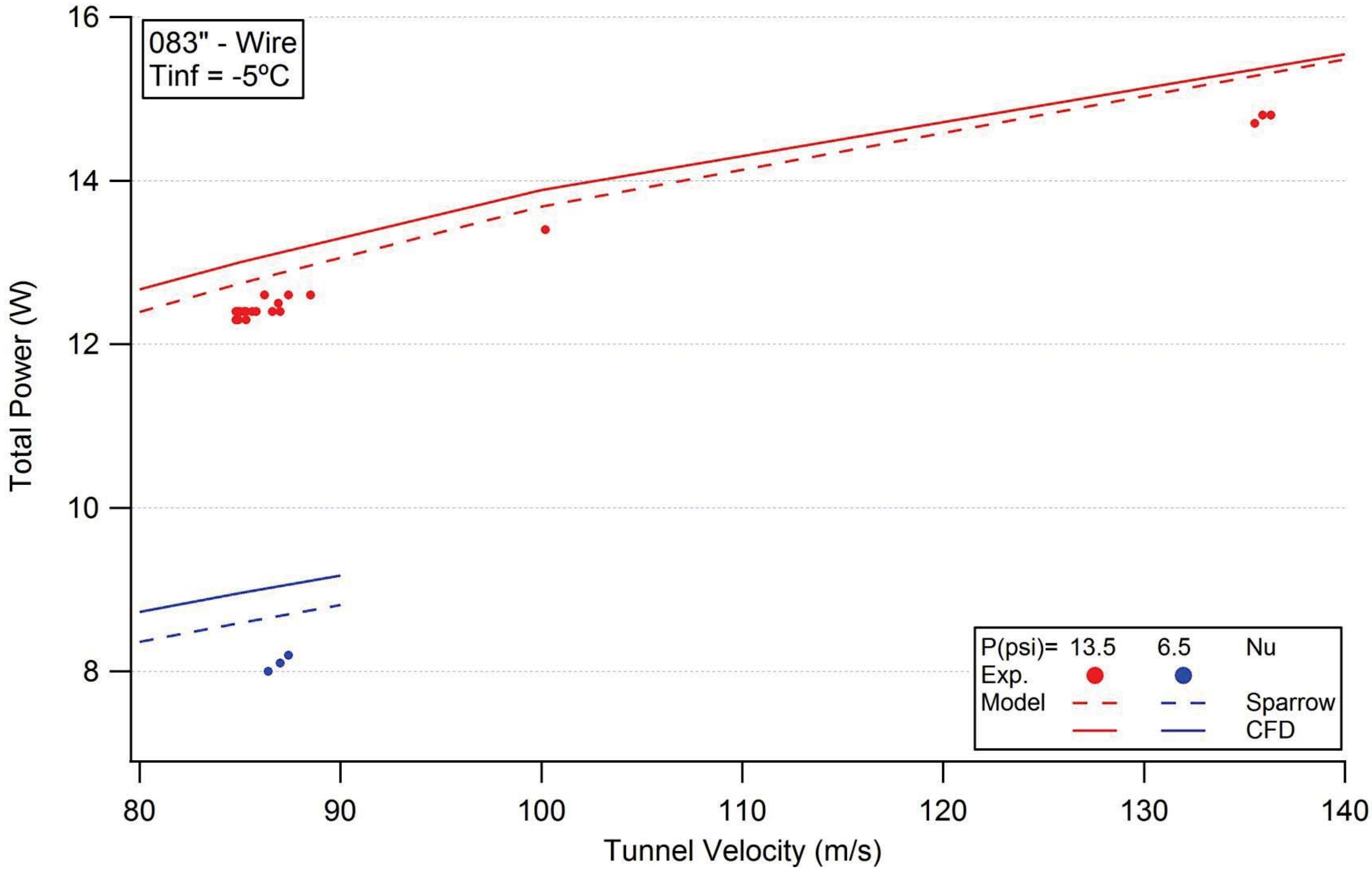
Experimental Data – Dry



Model vs. Experiment – Dry

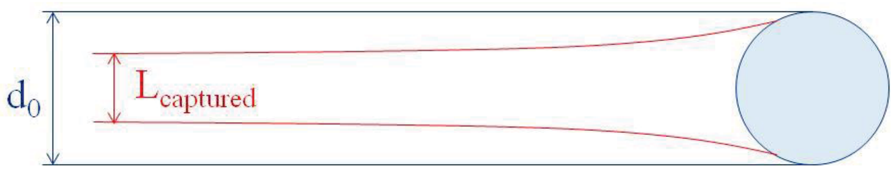


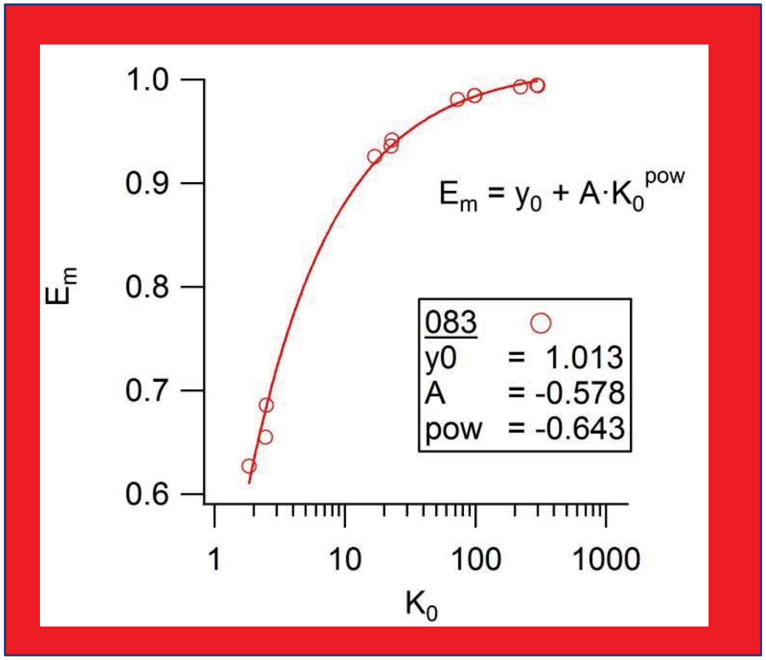
Model vs. Experiment – Dry



Heating & Evaporation Model

Data from Rigby et al. (2014)





LWC

Total Collection Efficiency

$$d\dot{m}_{LWC,\infty} = E_m \cdot \dot{m}''_{LWC,\infty} \cdot d_o \cdot dx$$

$$d\dot{q}_{wet} = \begin{cases} d\dot{m}_{LWC,\infty}\left(C_{P,LWC}\left[T_s - T_{LWC,\infty}\right] + \eta_w L_v\right), & T_s < T_b \\ d\dot{m}_{LWC,\infty}\left(C_{P,LWC}\left[T_b - T_{LWC,\infty}\right] + \eta_w L_v\right), & T_s \geq T_b \end{cases}$$

"Evaporation Efficiency"
(next slide)

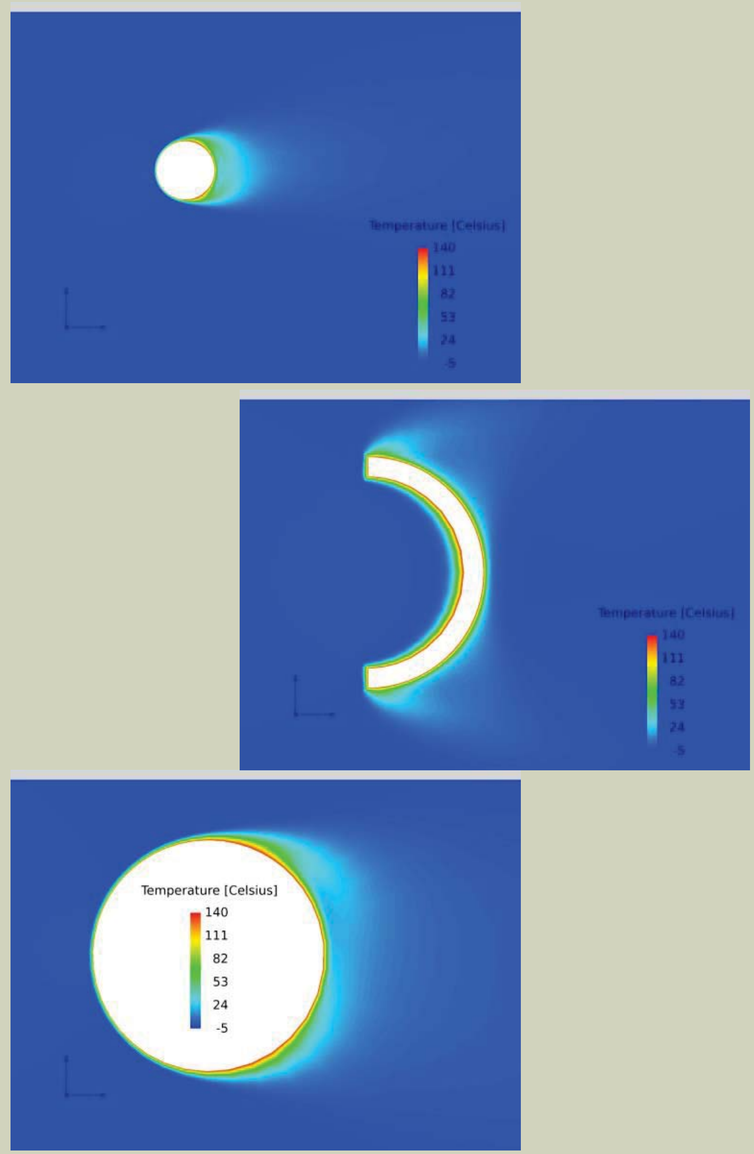
Evaporation Efficiency

- Needed a way to estimate fraction of water that does not evaporate
- Defined a parameter called evaporation efficiency, η

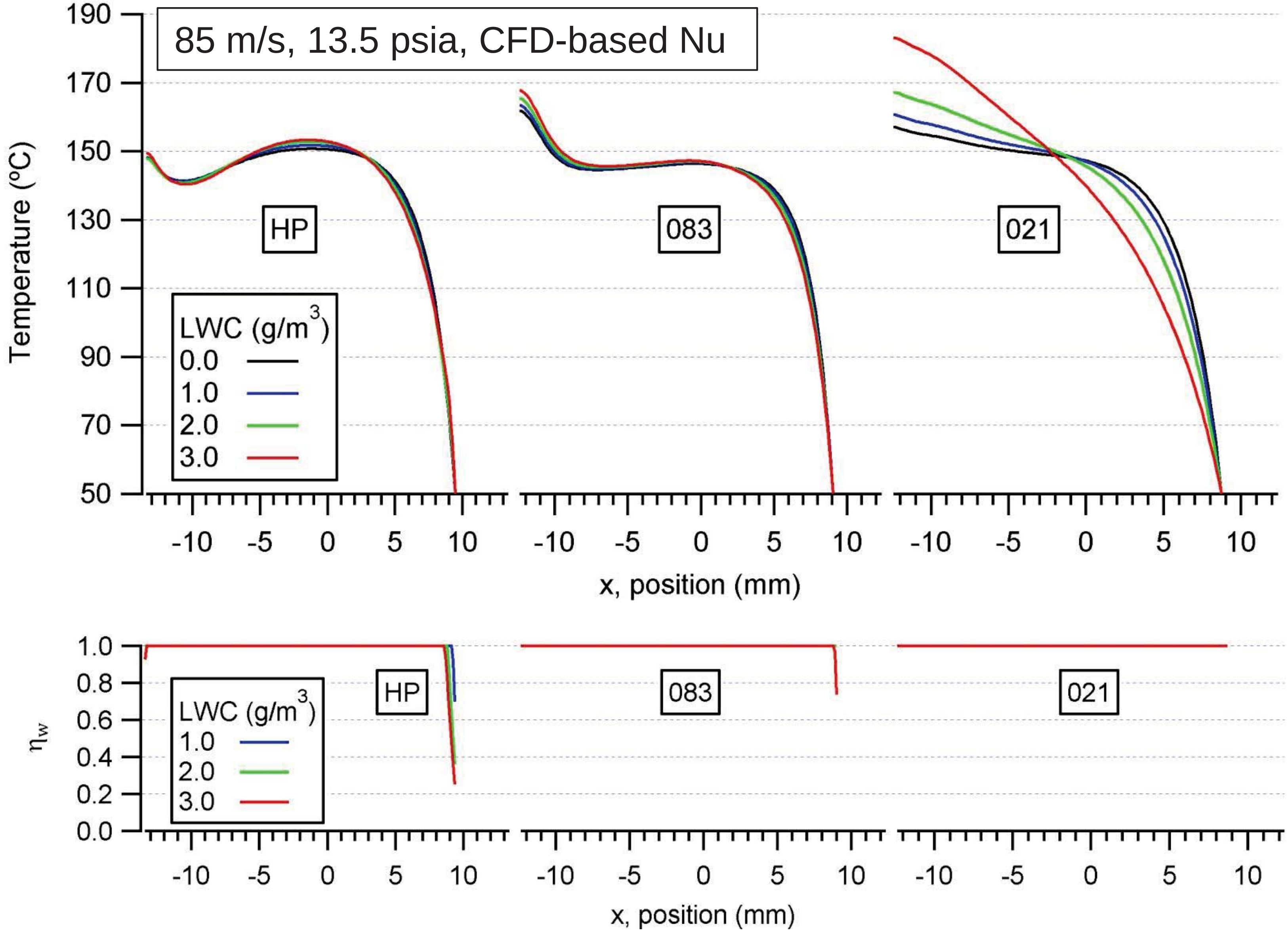
$$\eta = \frac{\textbf{evaporation potential}}{\textbf{incoming mass flux}} \qquad 0 \le \eta \le 1$$

- Use analogy of heat & mass transfer
  - Mass flux related to heat flux
- Evaporation area:
  - For 083,021 entire circumference
  - For HP, forward face of element
- Does not include bounce / splash

Temperature profiles from CFD

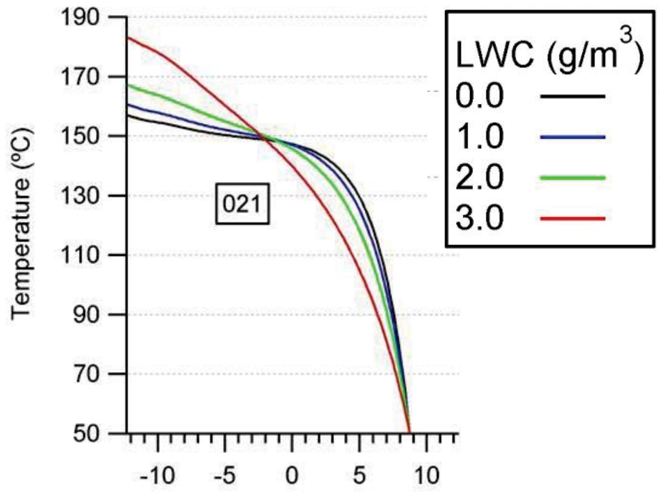


Effect of LWC on Temperature Profiles



Wet Power - Effect of Conduction Losses

$$P_{wet} = P_{total} - P_{dry}$$



Term	Dry	Wet
LWC (g/m^3)	0	3
$\dot{q}_{gen}$ (W)	6.34	13.61
$\dot{q}_{conv}$ (W)	-6.05	-6.05
$\dot{q}_{cond}$ (W)	-0.28	-0.14
$\dot{q}_{rad}$ (W)	-0.01	-0.01
$\dot{q}_{wet}$ (W)	0	-7.41

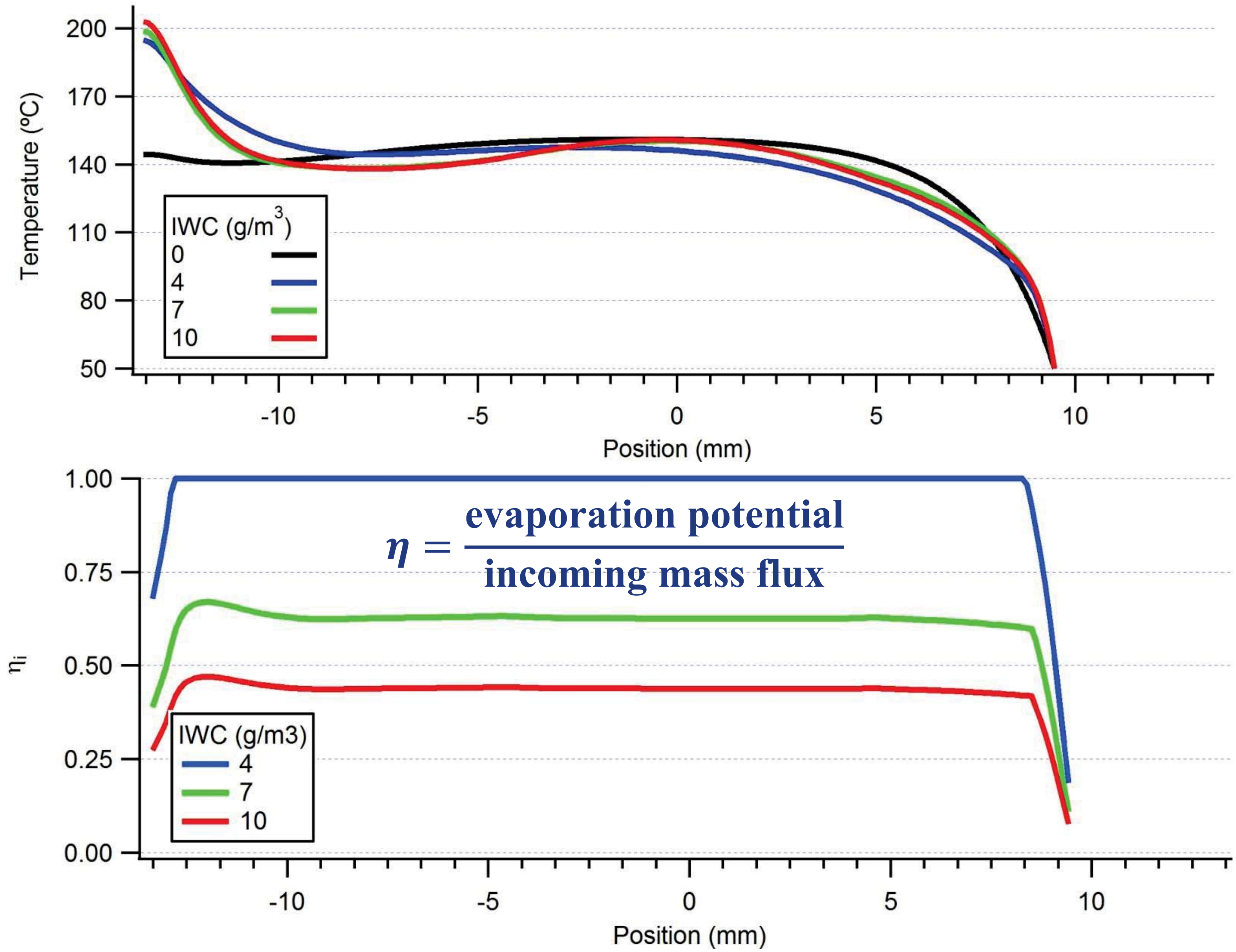
- Traditional wet power calculation:

$$P_{wet} = 13.61\,W - 6.34\,W = 7.27\,W$$

However, energy needed to evaporate LWC was 7.41W (1.9% diff)

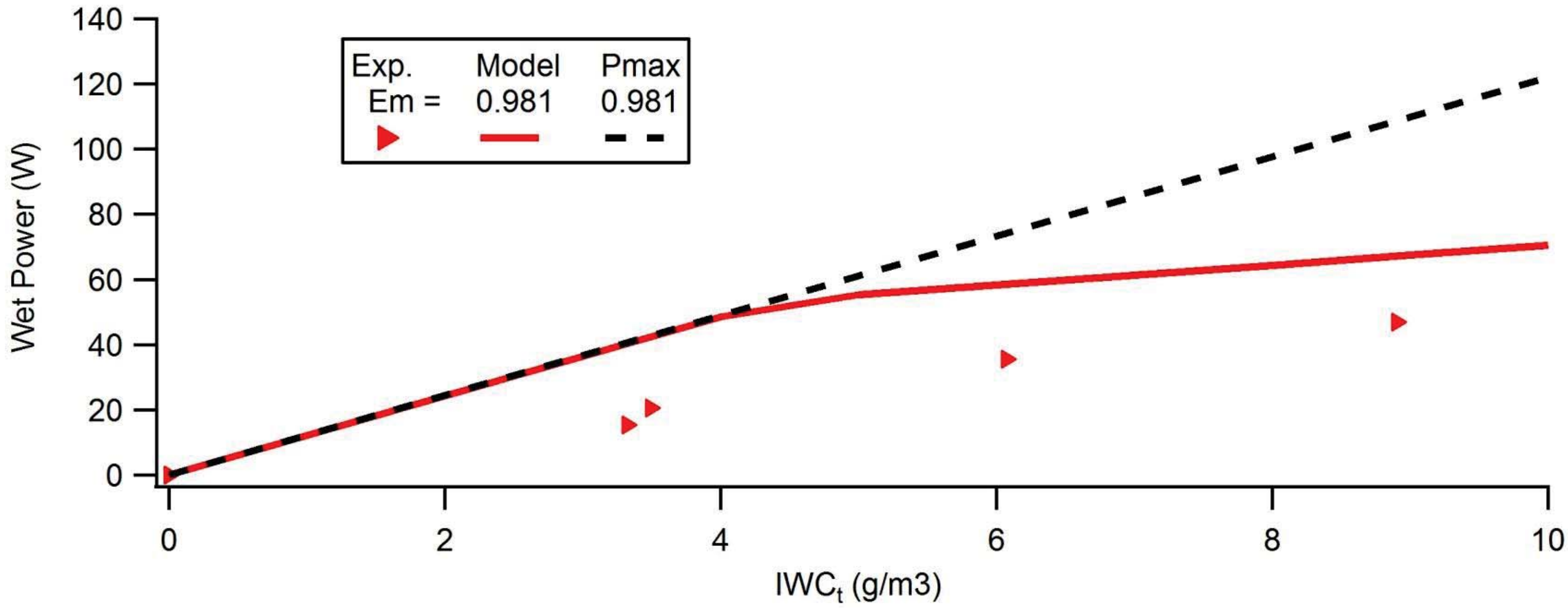
Under measurement is due to conduction loss differences

IWC



200
170
140
110
80
50
Temperature (ºC)
IWC (g/m3)
0
4
7
10
-10
-5
0
5
10
Position (mm)
1.00
0.75
0.50
0.25
0.00
ηi
η = evaporation potential / incoming mass flux
IWC (g/m3)
4
7
10
-10
-5
0
5
10
Position (mm)

Wet Power vs. IWC



Conclusions (1 of 2)

- **Developed steady-state hot-wire thermal model**
  - Includes resistive heating, convection, axial conduction, radiation, and water/ice evaporation
- **Examined:**
  - Temperature & power variation along the wire
  - Steady-state power
- **Model compared to SEA multi-wire probe data**
- **For dry conditions:**
  - Matched experiment to within:
    - 5.5% for 021
    - 9.2% for 083
    - 14% for HP
  - Max. conduction loss ~ 4% of total power for conditions examined

Conclusions (2 of 2)

- **Wet conditions:**
  - Introduced "evaporation potential" to estimate % water evaporated
    - Needs validation
  - LWC:
    - Affected temperature profile of 021 most significantly;
    - In all cases, high evaporation potential, effect minimal
    - Conduction losses can be different dry vs. wet
      - For 021 at 3 $g/m^3 \rightarrow$ 1.9% difference in P_{wet} measured vs. actual
  - IWC (HP only)
    - Model suggests a non-linear behavior of wet power and IWC_t
      - Below 4 g/m^3, linear relationship
      - Above 4 g/m^3, non linear due to incomplete evaporation everywhere along wire
    - Limited available experimental data to see if trend is correct
    - Bouncing or splashing-type loss present in experiment complicate interpretation
- **Further examination & development of model planned**

Acknowledgments

- This work is supported by the Atmospheric Environment Safety Technology Project (AEST) in the NASA Aviation Safety Program.

- Author acknowledgements:
  - Lyle Lilie and the staff of Science Engineering Associates
  - William Wright
  - Colin Bidwell
  - Tadas Bartkus