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Recent Advances in the LEWICE Icing Model

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Outline

- Thermal Model Modifications
- Thermal Model Validation
  - Comparison with Thermal Scaling Data
- Conclusions from Thermal Analysis
- Mixed Phase Additions
- Mixed Phase Calibration
  - Comparison with RatFac Data
- Conclusions From Ice Crystal Analysis

Thermal Model Additions

- **Myers Water Film Model**

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left[\frac{h^3}{3\mu_w}\left(\sigma\frac{\partial^3 h}{\partial x^3}+G_3\frac{\partial h}{\partial x}-G_1\right)+\tau_w\frac{h^2}{2\mu_w}\right]=\frac{\rho_a}{\rho_w}\beta V_\infty$$

- **Surface Water Shedding Model (calibrated)**

$$\frac{\dot{m}_{shed}}{\dot{m}_{runback,in}}=\frac{We-We_c}{We} \qquad We=\frac{\rho_a V_a^2 x_k}{\sigma} \qquad We_c=200+5*10^5 x_k$$

- **Enhanced Evaporation**
  - **Chilton-Colburn analogy underestimates evaporation rate by 30%**

Process for Comparison

- **Determine Internal Heat Transfer Coefficient from Dry Cases**
  - **All Cases Use Same Coefficients**

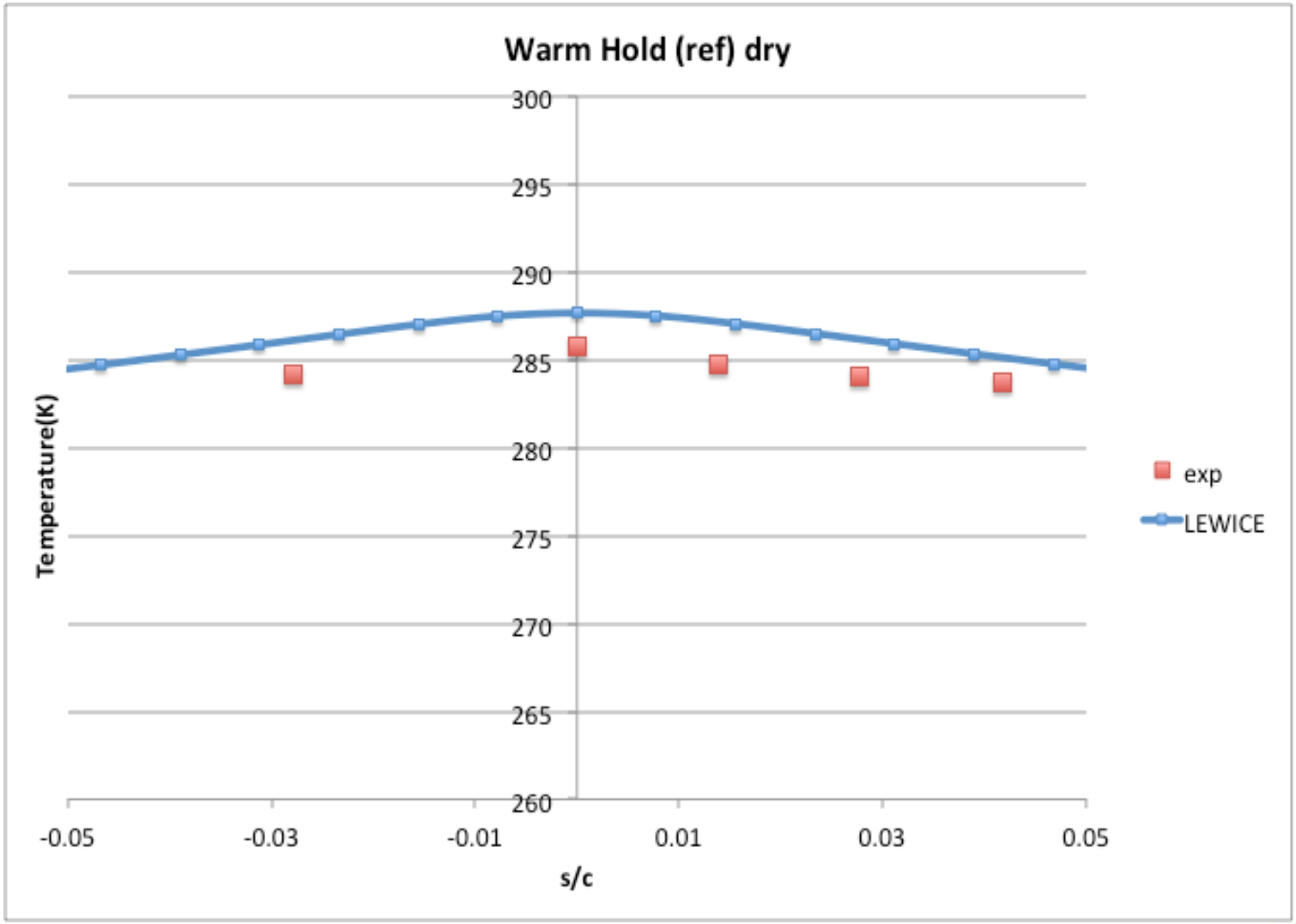
$$Nu = 0.004 \,\mathrm{Re}\,\mathrm{Pr}^{1/3} \left(\frac{z_n}{d_h}\right)^{-0.22} \left(\frac{x}{d_h}\right)^{-0.38}$$

- **External Heat Transfer Coefficient is Forced Laminar Where There is No Ice**
- **Run All Dry Cases To Ensure Correlation Matches**
- **Run Wet Cases for Validation**

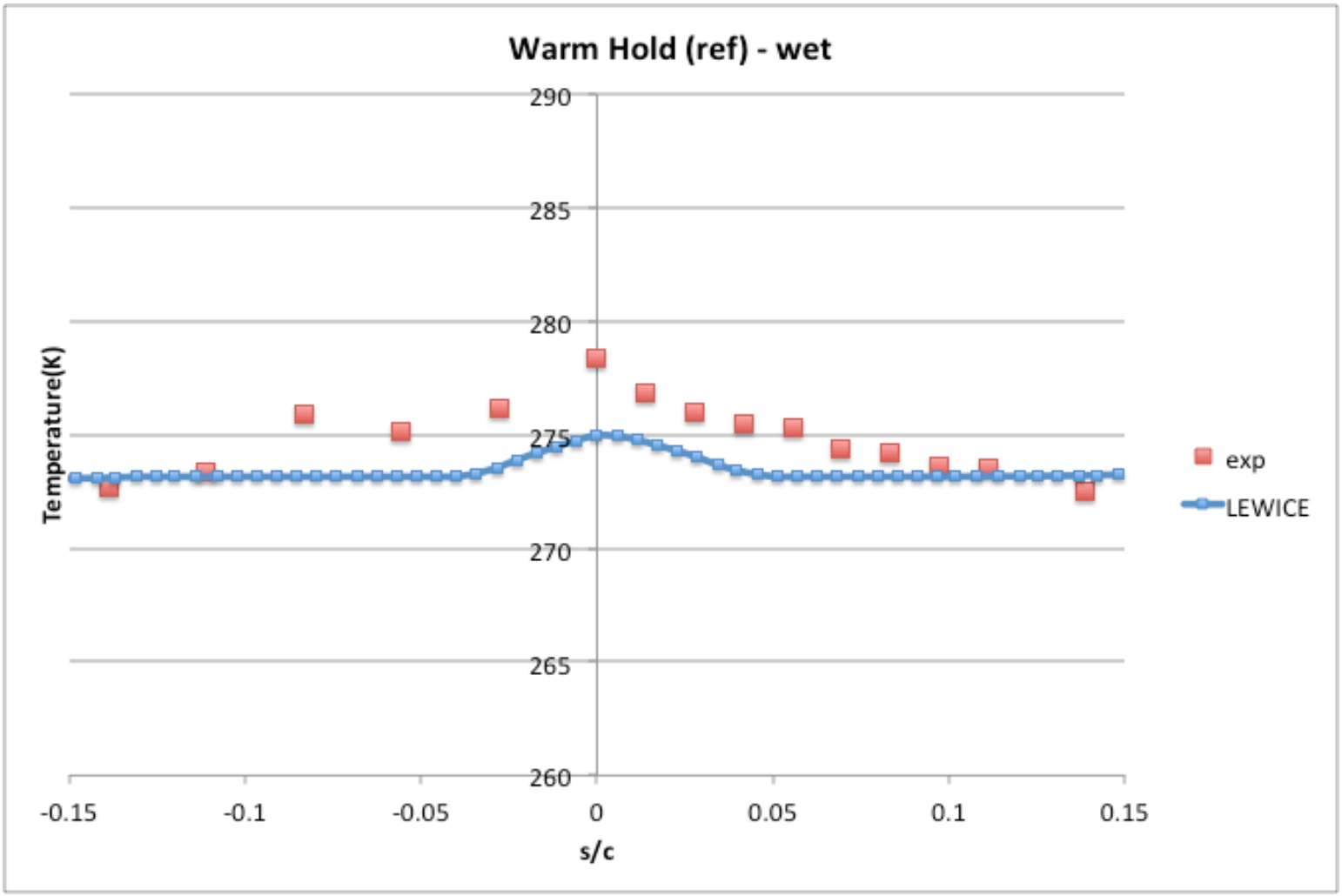
Conditions Used For Thermal Comparison

Case	P(Pa)	V(m/s)	T(K)	LWC	MVD	AOA	t(min)
Warm Hold(Ref)	57295	92.7	264.5	0.5	20	0	7
Warm Hold(Scale)	98525	54.3	266.9	0.85	27.8	0	7
Descent(Ref)	69981	92.7	253.1	0.15	20	0	7
Descent(Scale)	97422	66.8	254.9	0.21	24.5	0	7
Cold Hold(Ref)	57295	92.7	247.4	0.15	20	0	10
Cold Hold(Scale)	98318	54.6	245.5	0.25	27.8	0	10

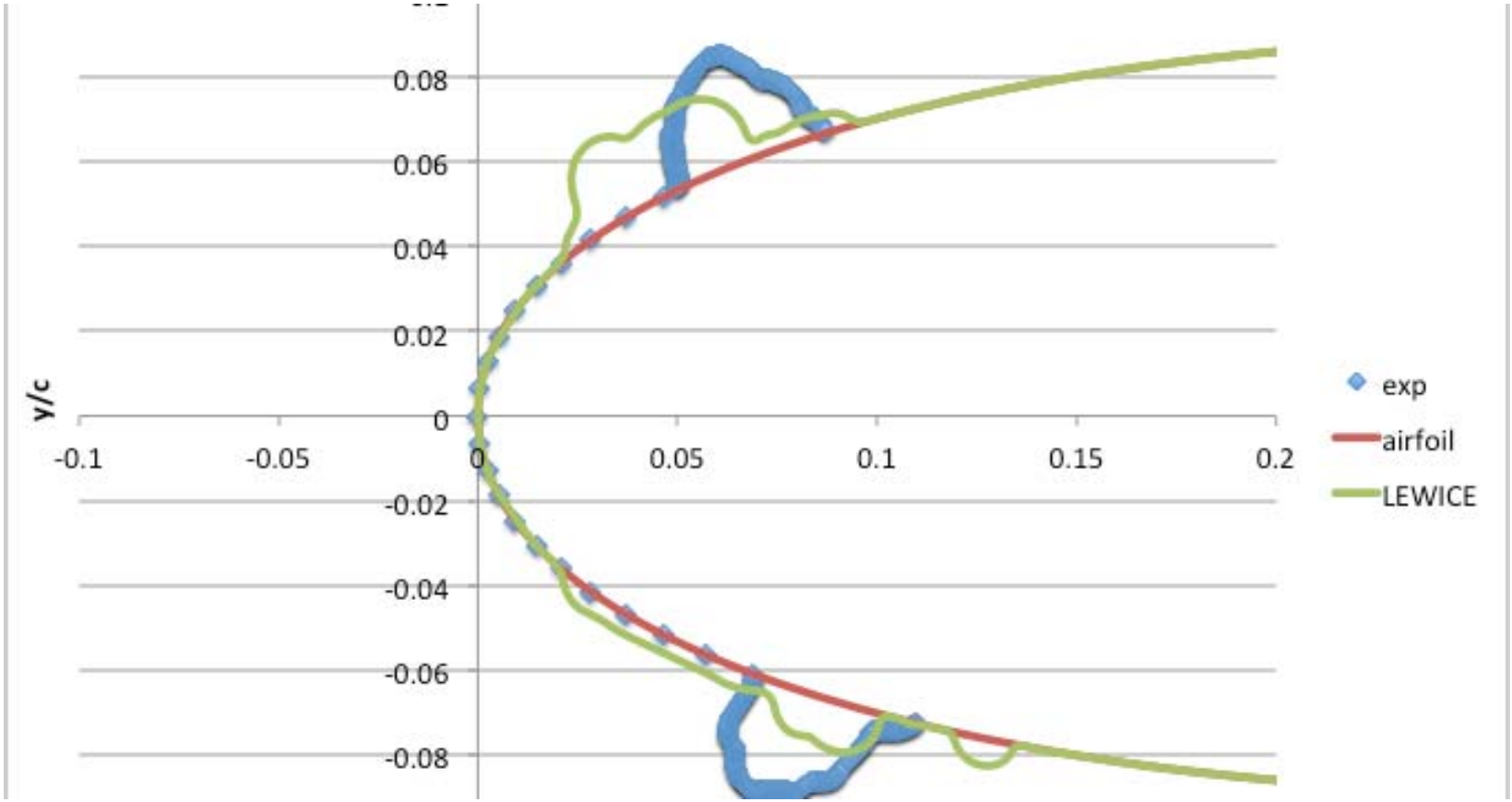
Warm Hold (Ref) - Dry



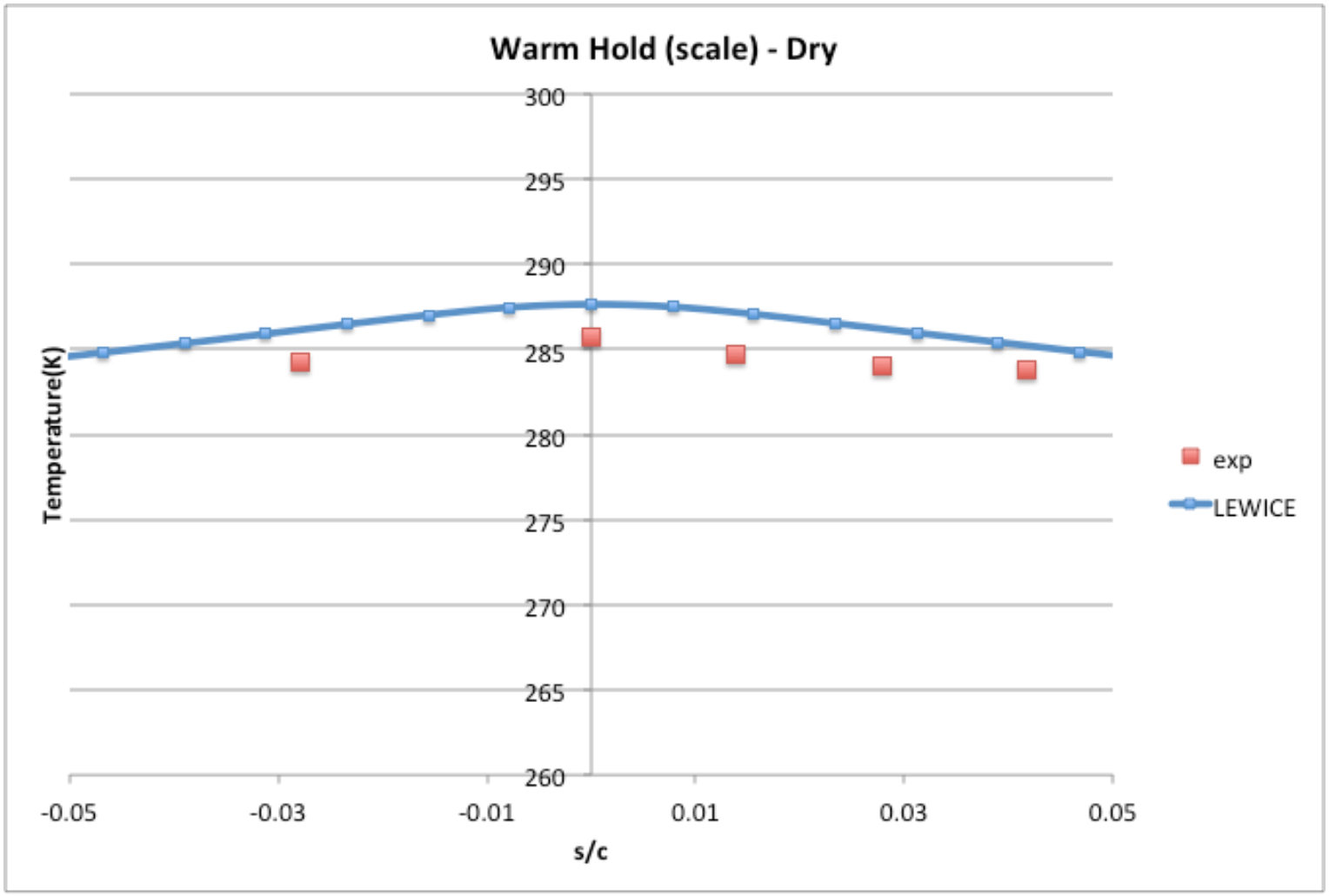
Warm Hold (ref) - Wet



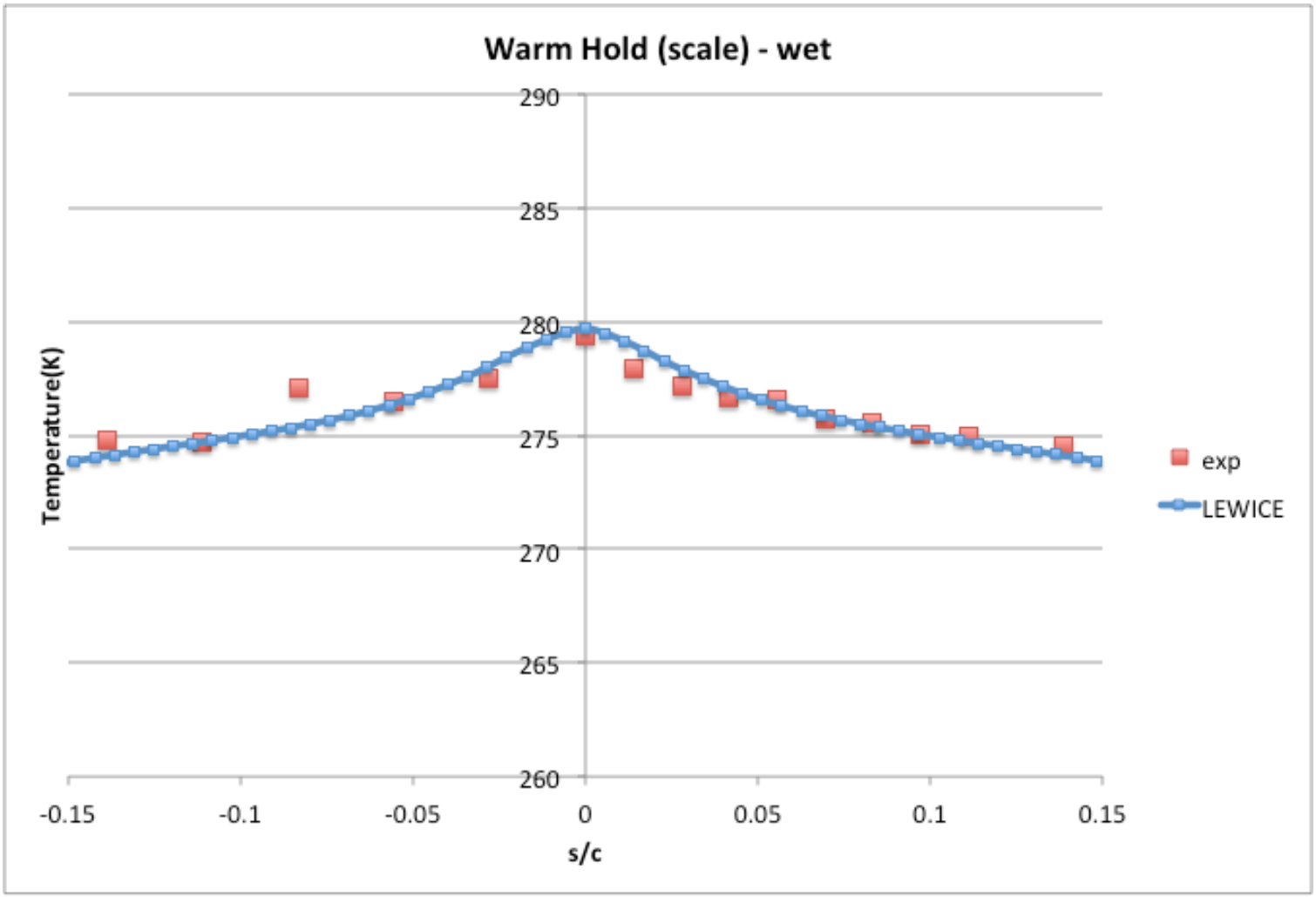
Warm Hold (Ref) Ice Shape Comparison



Warm Hold (Re Scale) - Dry



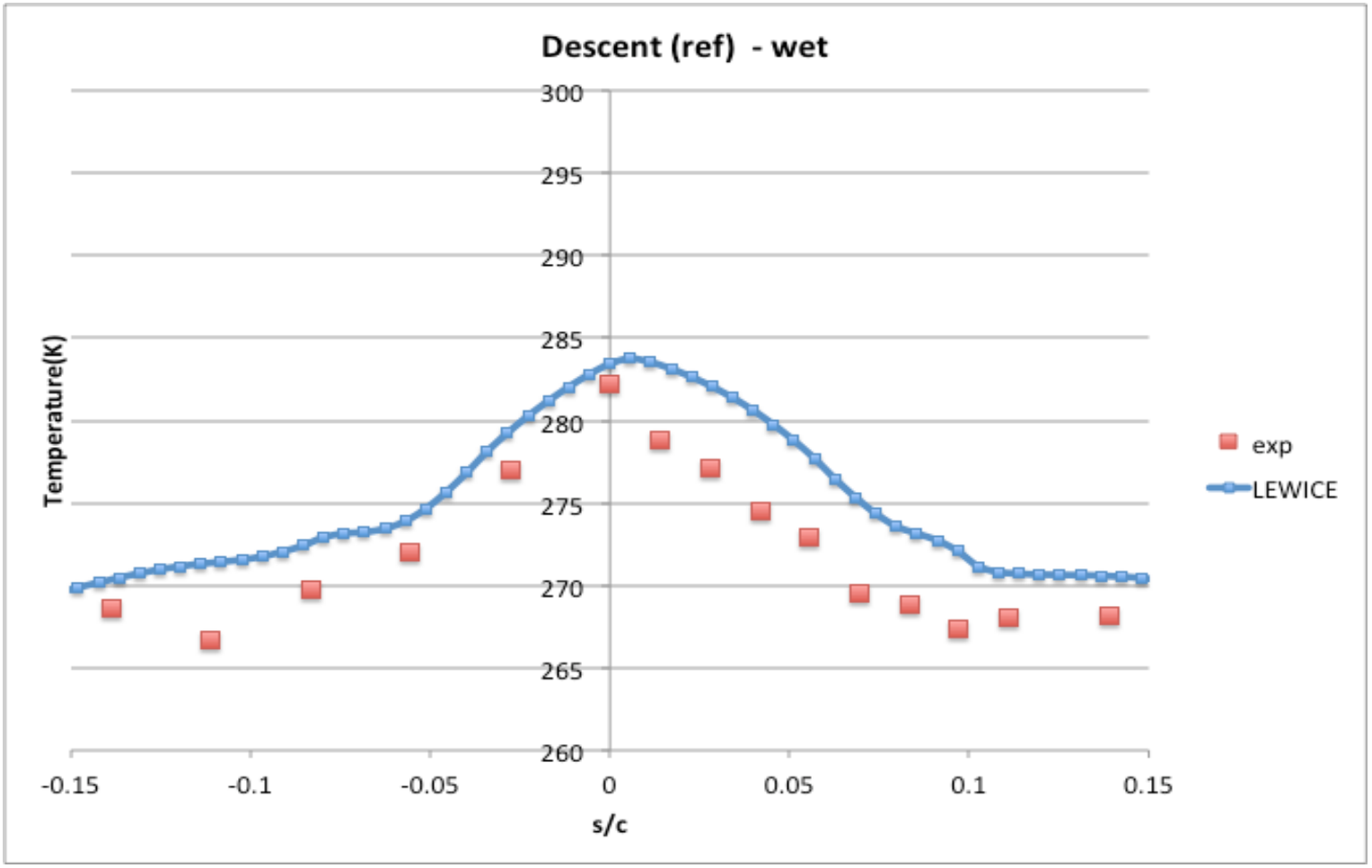
Warm Hold (Re Scale) - Wet



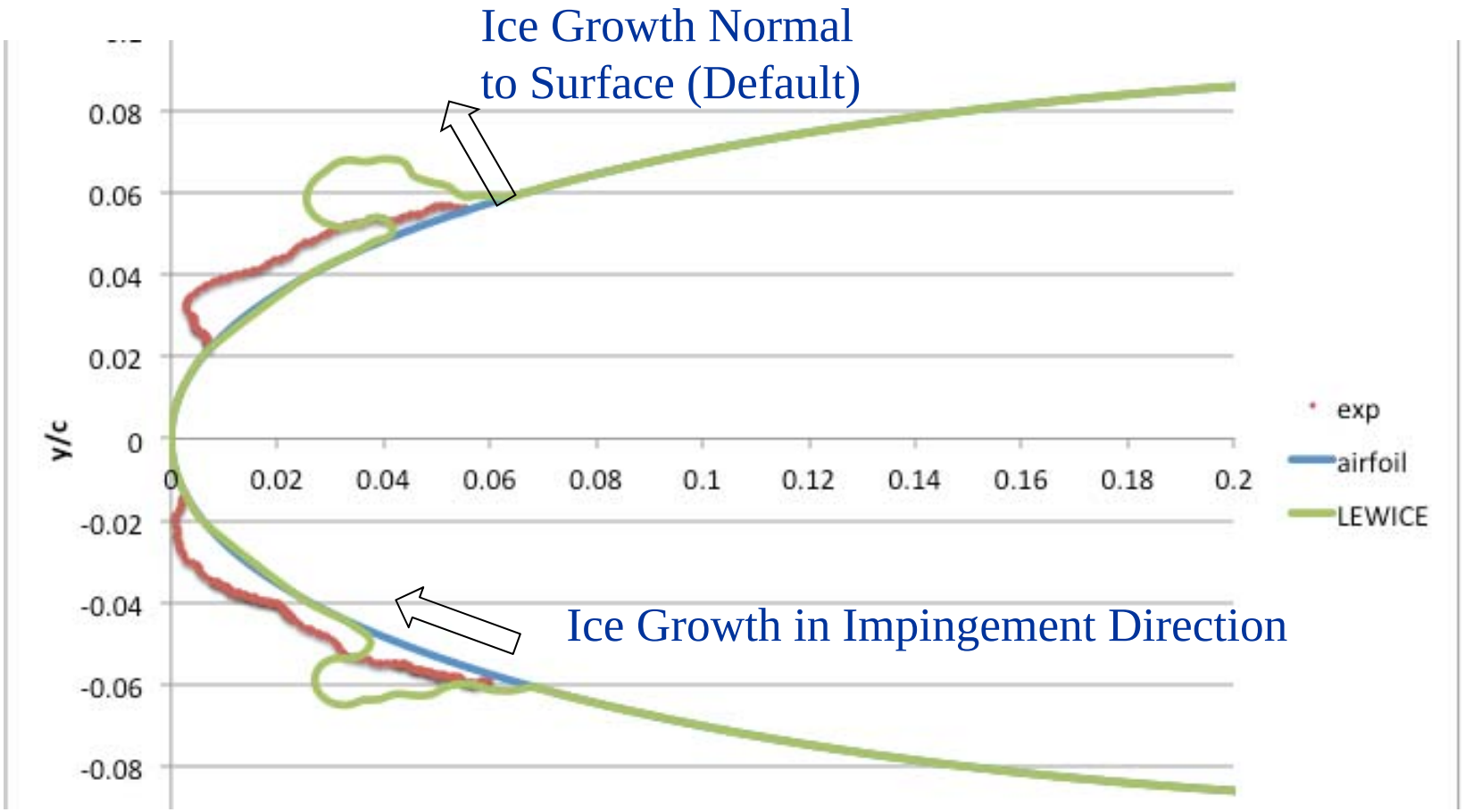
Warm Hold (Re Scale) Ice Shape

- **No Ice from Experiment nor from LEWICE**

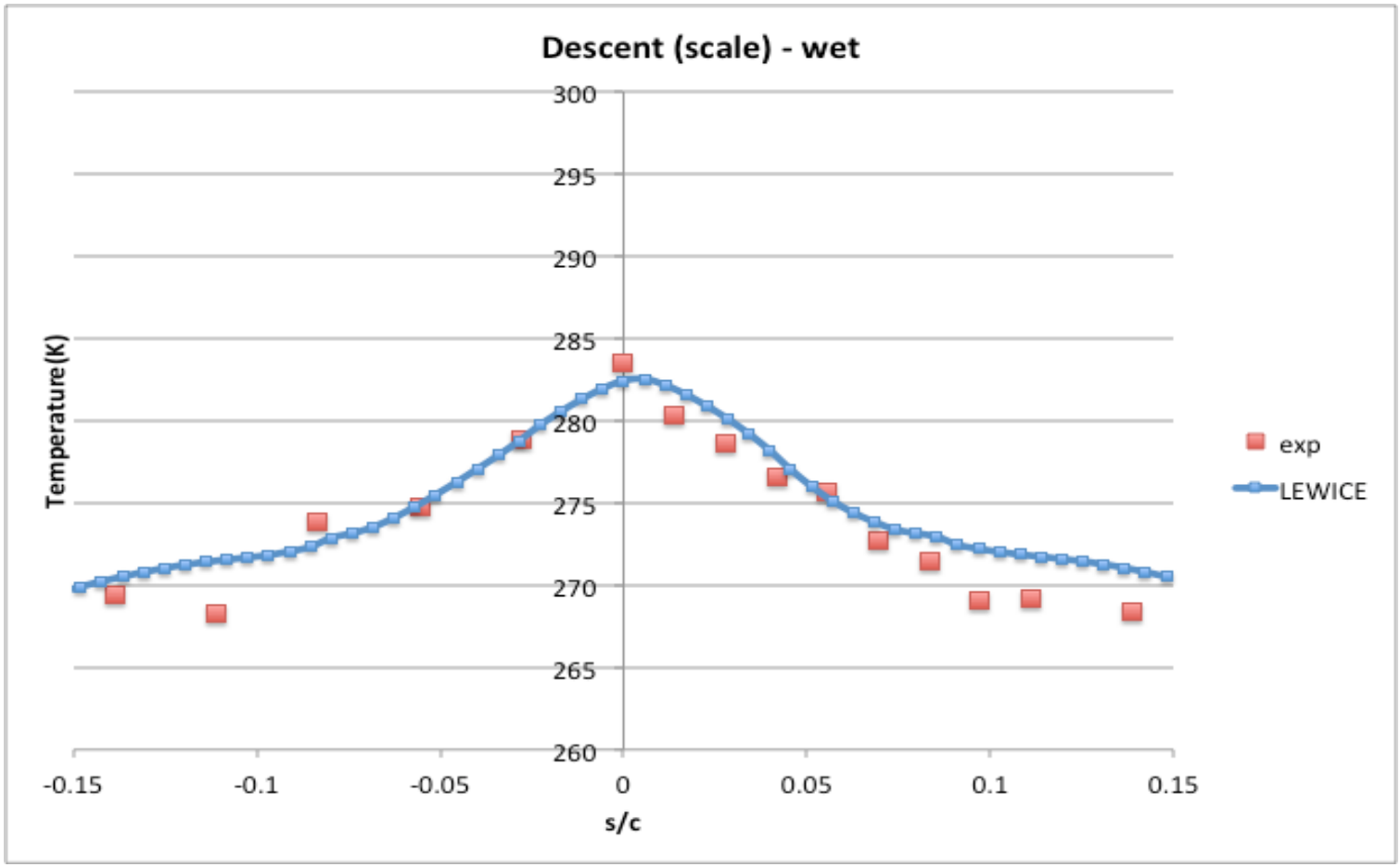
Descent (Ref)


Descent (ref) - wet
Temperature(K)
300
295
290
285
280
275
270
265
260
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
s/c
exp
LEWICE

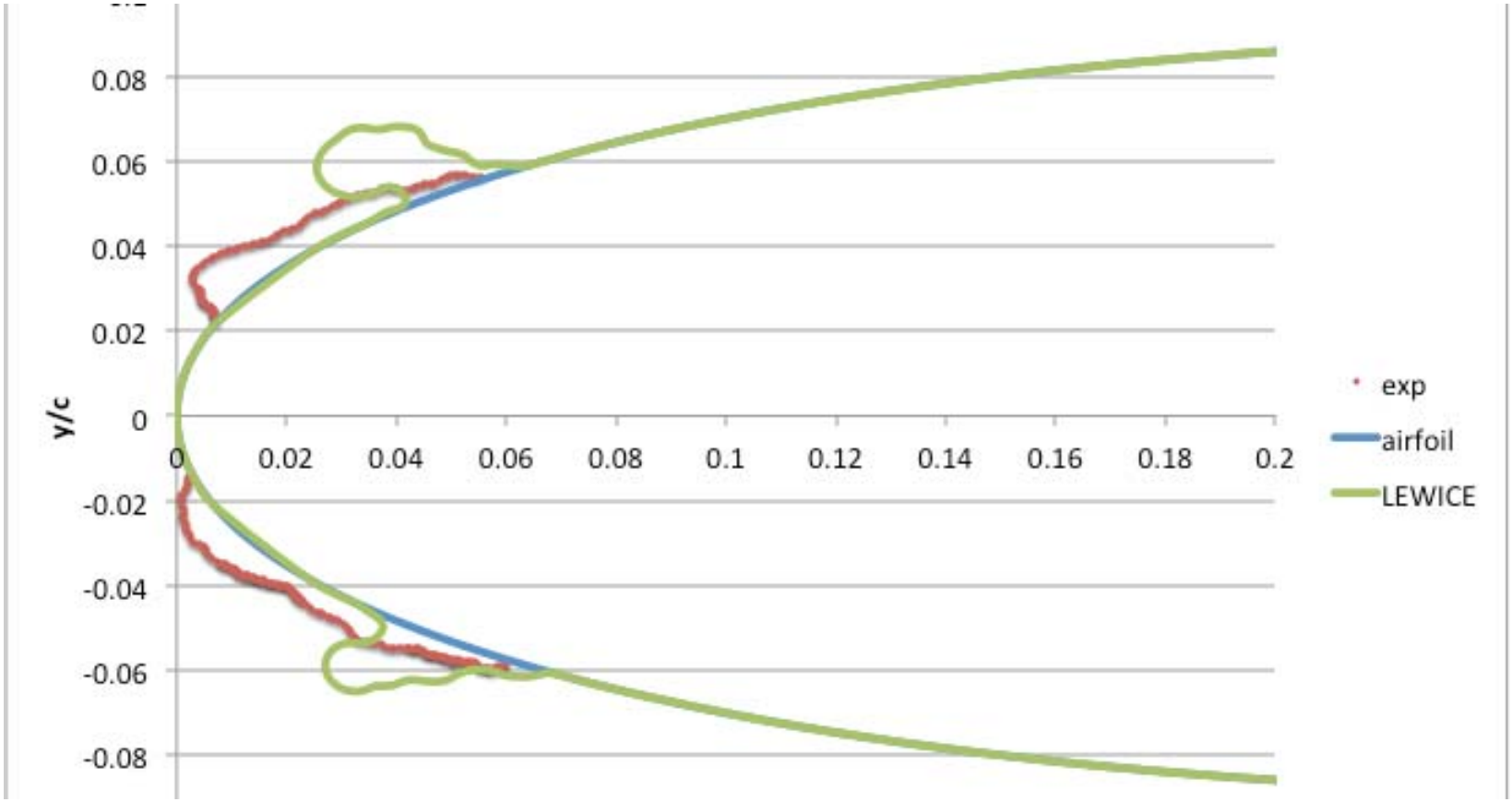
Descent (Ref)


Ice Growth Normal
to Surface (Default)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
y/c
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
exp
airfoil
LEWICE
Ice Growth in Impingement Direction

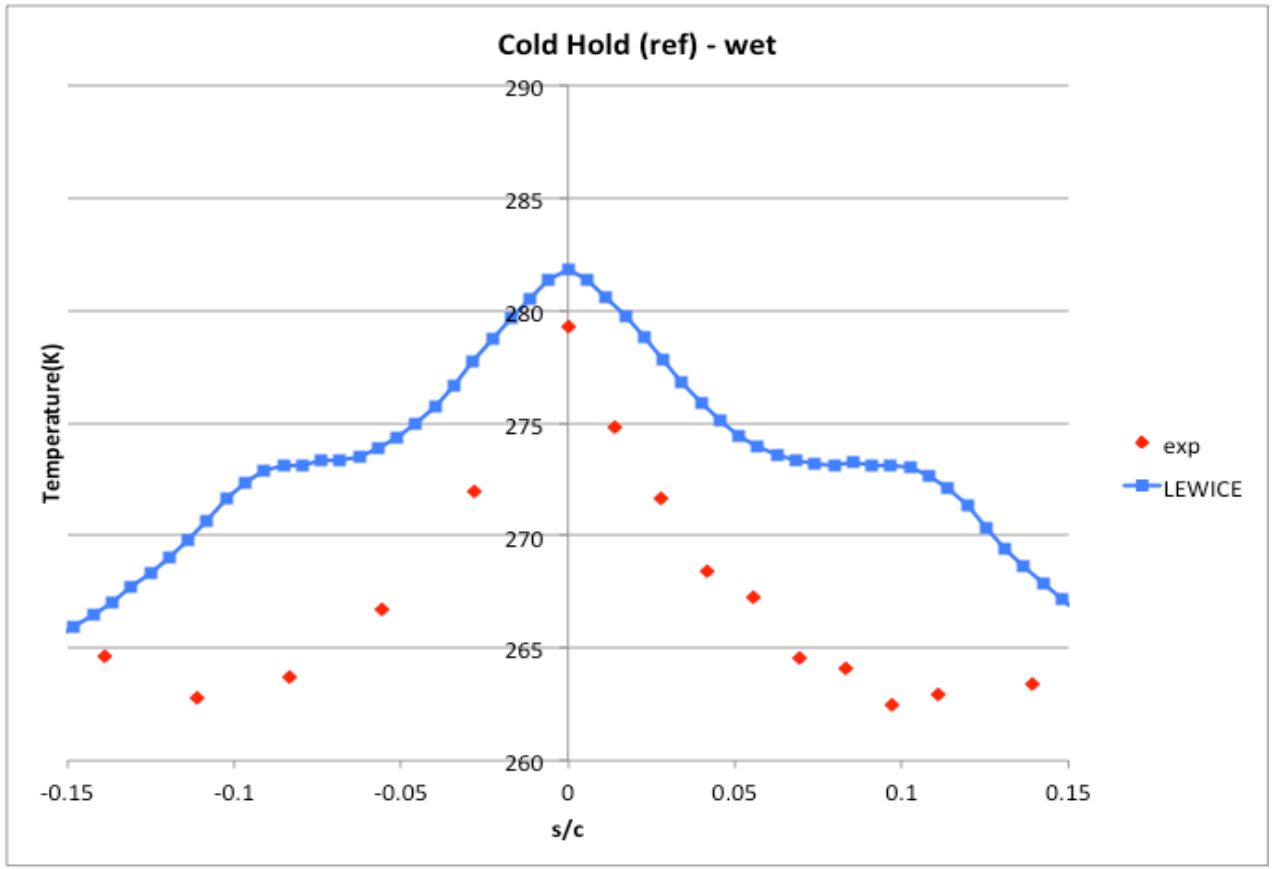
Descent (Re Scale)



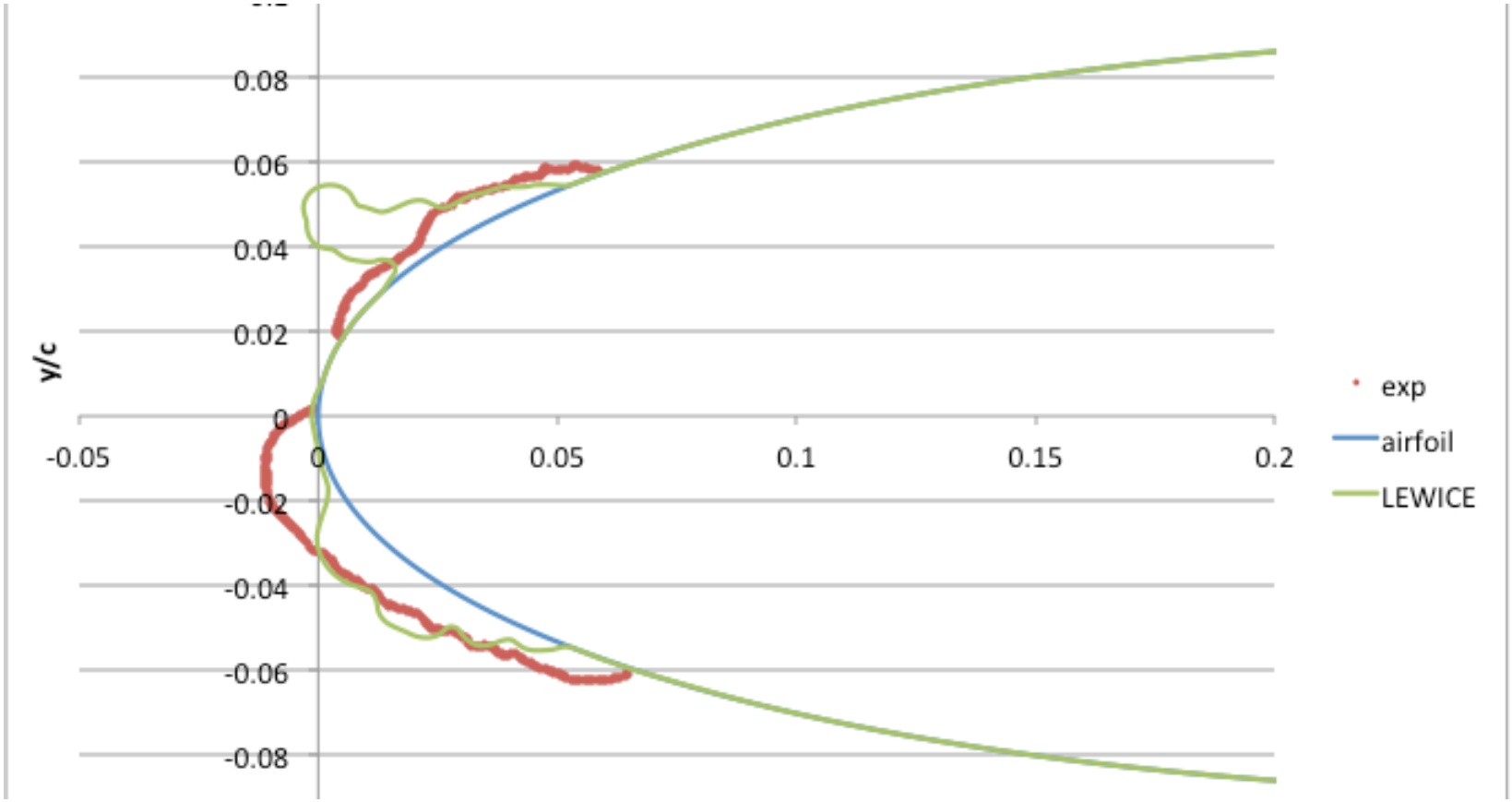
Descent (Re Scale)



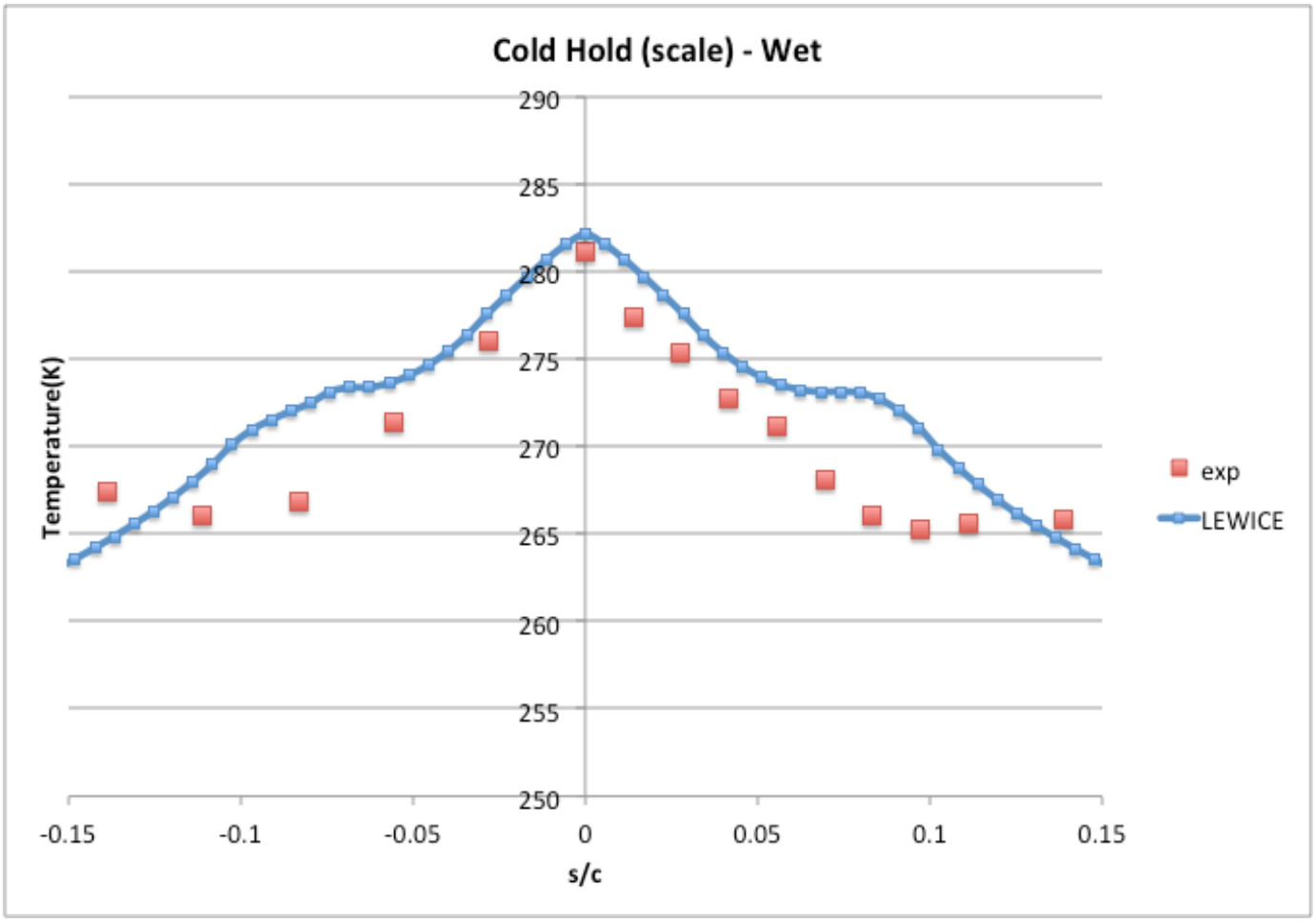
Cold Hold (Ref) - wet



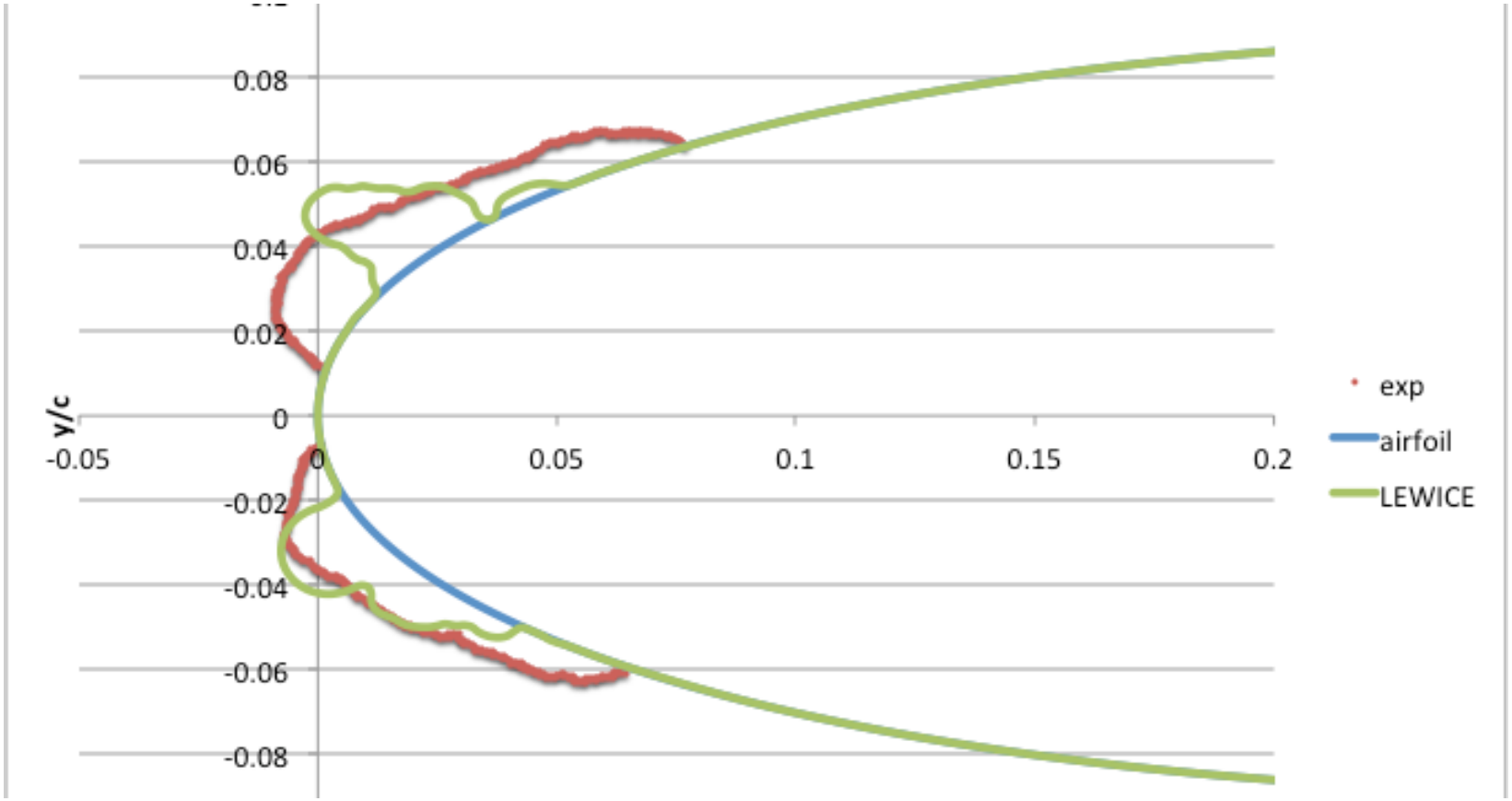
Cold Hold (Ref)



Cold Hold (Re Scale) - wet



Cold Hold (Re Scale)



Observations from Thermal Analysis

- Temperature Prediction is Very Good to Excellent for Most Cases
- Warm Hold Cases Show Predicted Runback Ice Forward of Experiment
  - Peak Ice Thickness Higher for LEWICE
- Descent and Cold Show Predicted Runback Ice Forms Slightly Behind Experiment
  - Peak Thickness Higher for LEWICE, Especially Upper Surface
- Ice in Experiment Grows Toward Leading Edge While LEWICE always grows Ice Normal to Surface
- Further Refinement of Runback Model May Be Necessary
- External Heat Transfer Coefficients for Residual Ice Shapes Need to Be Separately Validated

Ice Breakup Model

- **Breakup Threshold (Hauk)**

$$V_{imp} \geq \frac{0.45}{\sin\alpha\sqrt{d}}$$

- **Sticking Efficiency (Currie)**

$$\frac{m_b}{m_o} = \left(1-\xi\cos\left(\alpha_{imp}\right)\right)\left(0.57+7.5*10^{-4}\left[V_{imp}\cos\left(\alpha_{imp}\right)\right]^{1.5}\right)$$

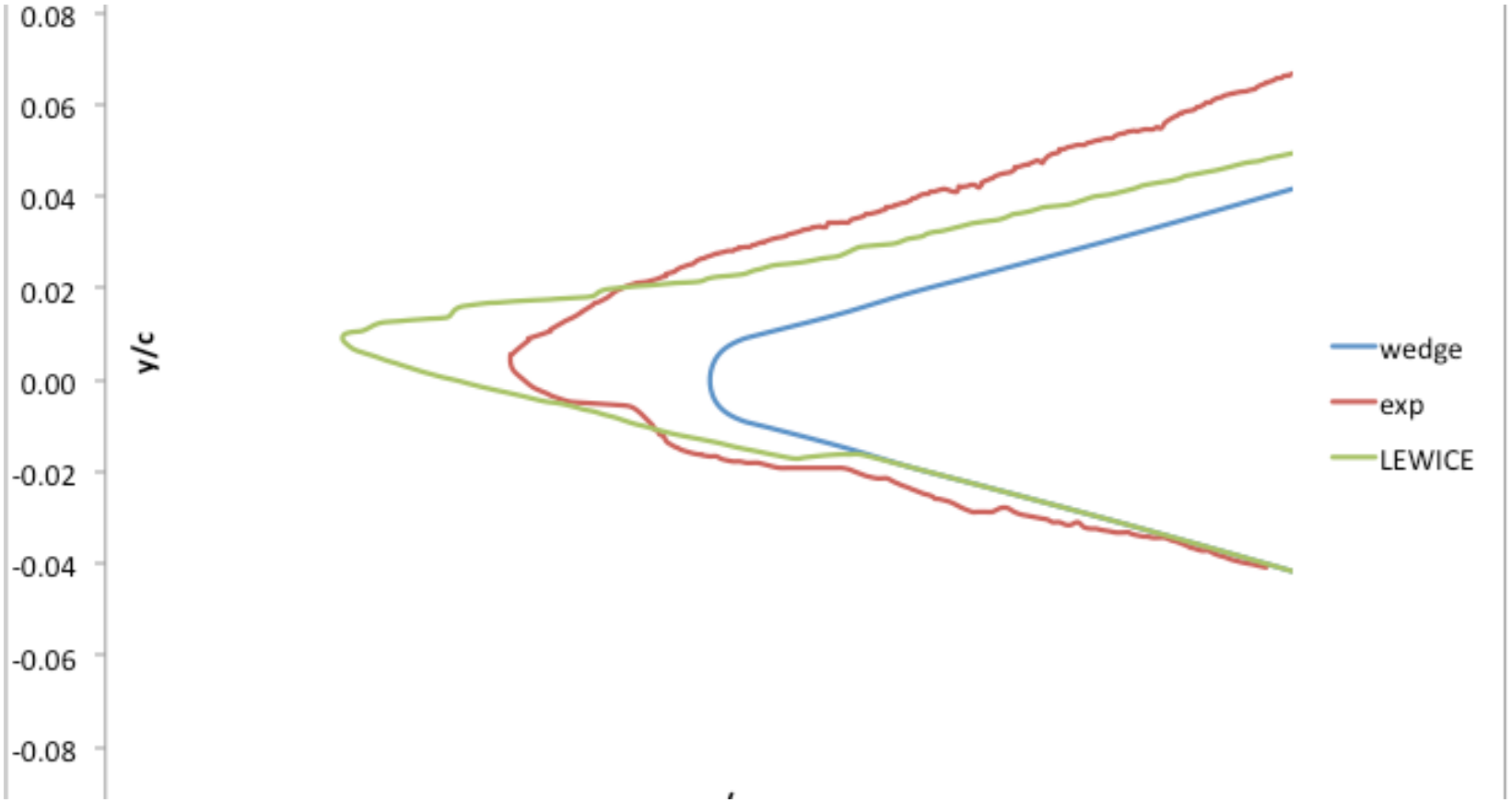
$$\xi = -0.1425+47.292TWC-1979.167TWC^2$$

  - **For TWC < 0.12 kg/m^3 and ξ = 0.14 for TWC > 0.12**

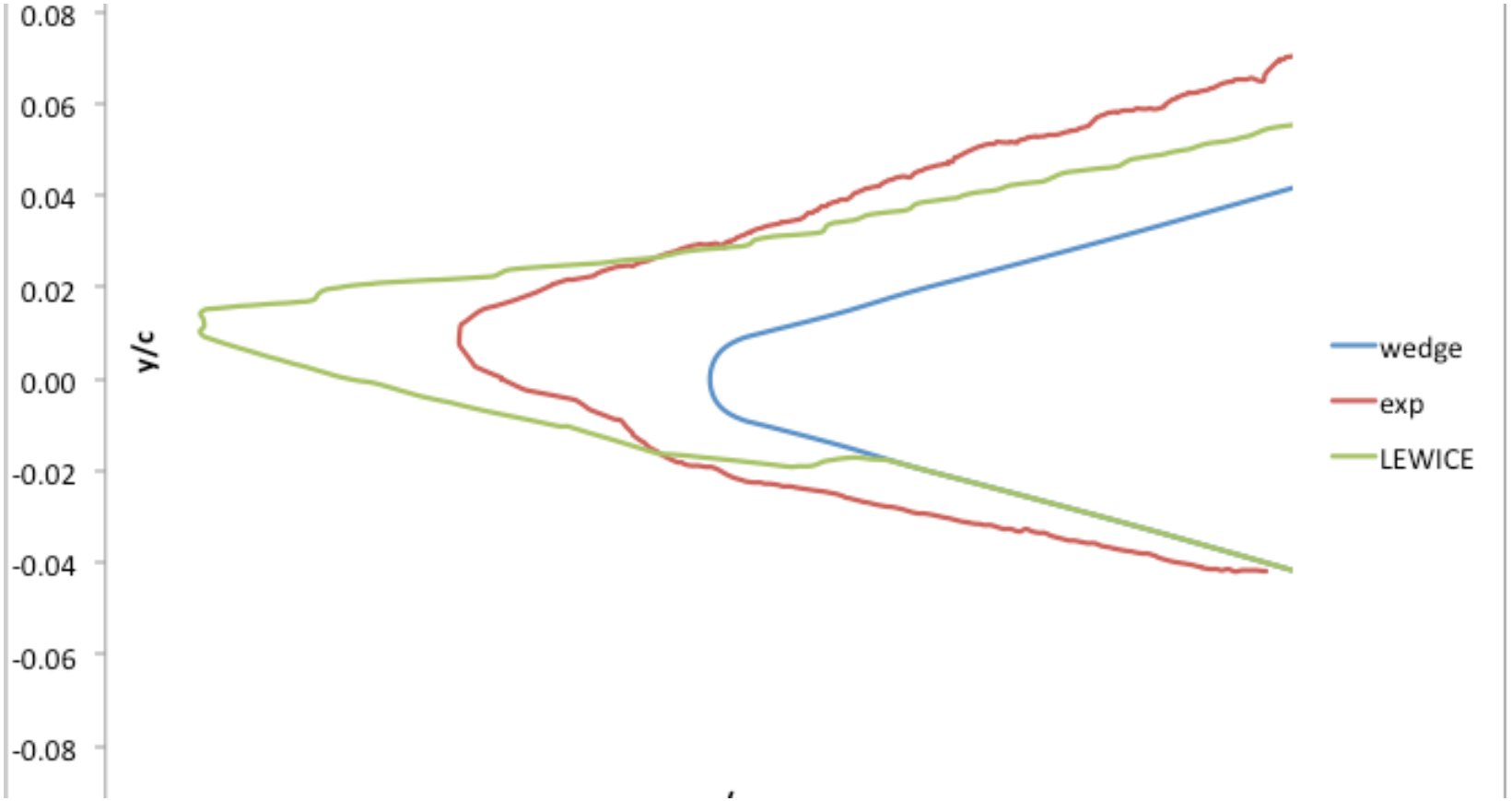
Conditions for Ice Crystal Comparison

Airfoil	Scan#	P	V	T	Sh	LWC	IWC	AOA	t(m)
Wedge	889	6.5	87.4	12.7	8.3	1.4	4.4	-6	3
Wedge	996	10	83.9	4.3	5.6	1.3	6.9	-6	3.5
Wedge	1003	10	84.1	3.8	5.2	1.9	7.3	-6	3.5
NACA 0012	796	6.5	86.2	7.2	5.9	0.6	4.9	0	3

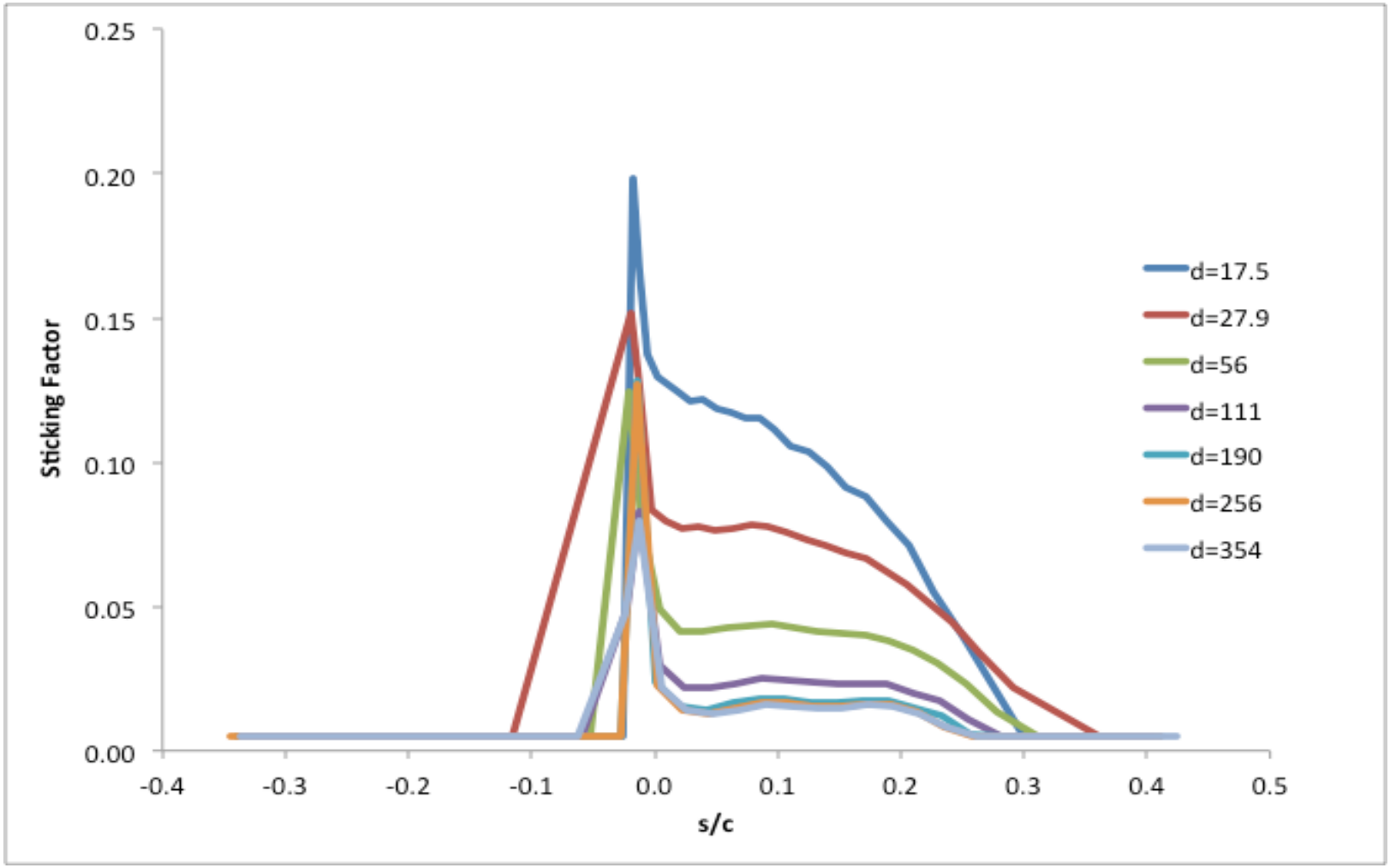
Ice Shape Prediction for Scan 996



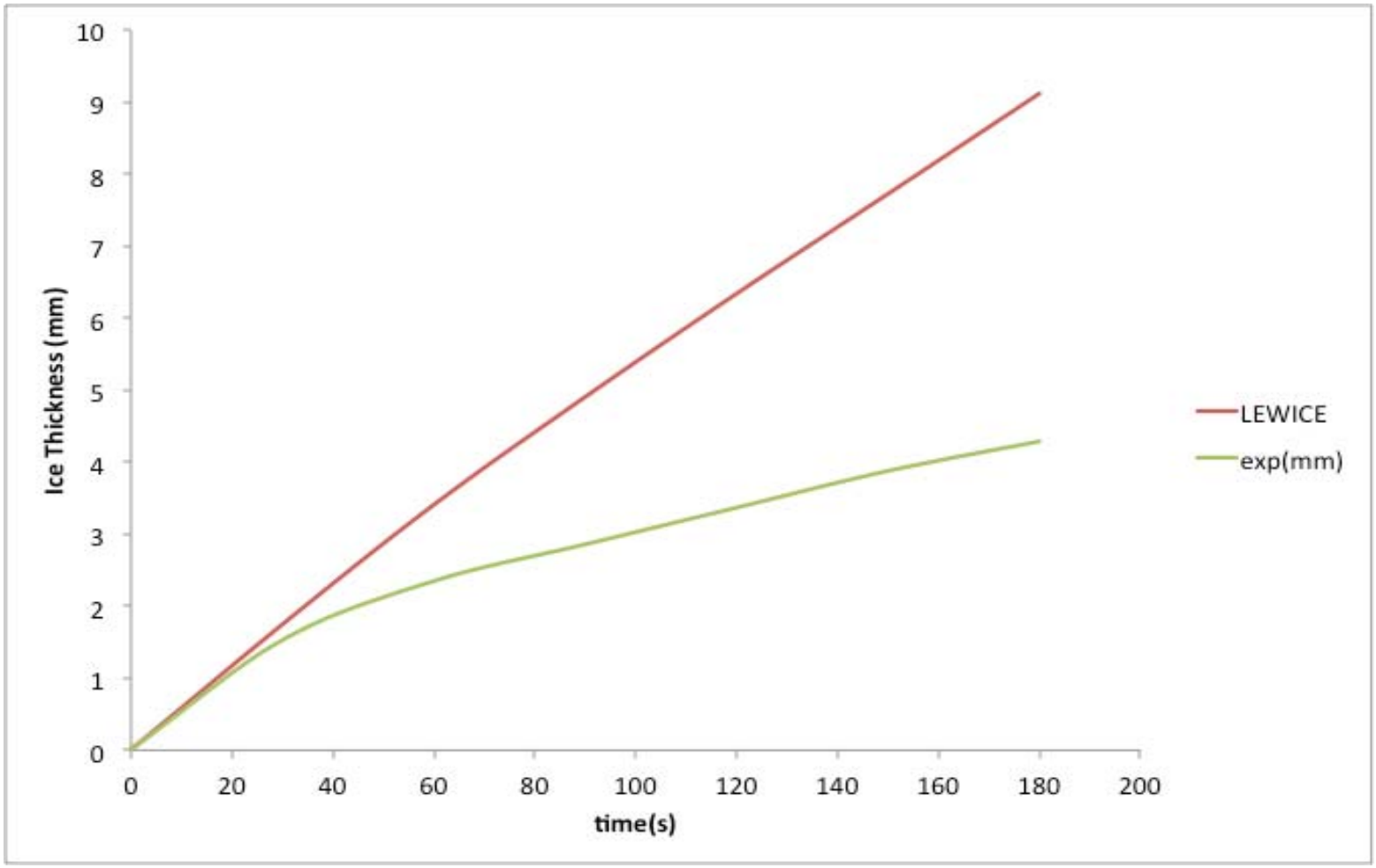
Ice Shape Prediction for Scan 1003



Sticking Efficiency on Wedge at Various Particle Sizes



Ice Thickness Prediction for Scan 796 (NACA0012)



Observations from Ice Crystal Comparison

- **Peak Thickness is Over Predicted by LEWICE while Extent is Under Predicted**
  - **Additional Erosion Effects may be Needed**
  - **Improved Model for Reimpingement of Ice Crystals**
- **Additional Data is Needed to Complete Model**