King-Probe Liquid Water Content (PLWCC)

Al Cooper

RAF Algorithm Review

Feb 16 2011

Development and Principle of Operation

King et al. 1978

- Hot wire maintained at constant resistance (temperature)

$$P = \pi l \lambda (T_W - T)\mathrm{Nu}$$
$$+ l d V \chi [L_v + c_w (T_w - T)]$$

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Basic Equation:

- Estimate heat dissipated in dry air

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Basic Equation:

- Estimate heat dissipated in dry air
- Remainder is heat required for vaporization

$$P = \pi l \lambda (T_W - T)\mathrm{Nu}$$
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Current Processing

Processing Steps

1. Find mean T
2. Find the thermal conductivity, viscosity, and dry-air density:
3. Calculate the Reynolds number:
4. Find the Prandtl Number
5. Find the dry-air term:
6. Find LWC from residual
7. Correct for baseline offset

Associated Equations

Calculate mean temperature between wire and air temperature, for use in determining heat-transport properties:

$$T_m = (T_W + T)/2$$

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Associated Equations

$$\lambda = 5.8 \times 10^{-5} \frac{398}{120 + T_m} \left(\frac{T_m}{T_0} \right)^{3/2}$$

$$\mu = 1.718 \times 10^{-4} \frac{393}{120 + T_m} \left(\frac{T_m}{T_0} \right)^{3/2}$$

$$\rho_d = \frac{p}{2870.5\, T_m}$$

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$$\mathrm{Re} = \frac{\rho V d}{\mu}$$

where ρ is the air density, V the true airspeed, d the diameter of the sensing wire, and μ the viscosity of air

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$$\mathrm{Pr} = c_p \mu / \lambda \simeq 0.735$$

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Associated Equations

$$P_{dry} = 0.26\,\mathrm{Re}^{0.6}\mathrm{Pr}^{0.37}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.25} \times \pi l \lambda (T_w - T)/0.239$$

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$$\chi = \frac{10^6 \times 0.239(P - P_{dry})}{l\,d\,V[597.3 + 373.16 - T]}$$

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Critique of Current Processing

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cf., Pruppacher and Klett:

$$\lambda = 0.0238+0.000071(T-T_0)$$

0°C: 5.87 vs 5.69; 20°C: 6.21 vs 6.03; -30°C: 5.34 vs 5.18

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$$\simeq 0.735$$

Almost no variability in the atmosphere; not worth including in fits and equations.

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Doesn't fit GV measurements at all.

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cf. King (1978):

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- Matches King equation only for $T_w = 100.01°\mathrm{C}$ (and $c_w = 1\mathrm{cal/g}$)
- Neglects T dep. of L_v(T).

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- OK, but would be better to correct Nu relationship and hence P_{dry} directly.

Equation for the Nusselt Number

Representation in terms of Re

$$\mathrm{Re} = \frac{\rho_d V d}{\mu(T_m)} = \frac{p V d}{R_d T_m \mu(T_m)}$$

$$\mathrm{Nu} = A_N Re^{\alpha} \text{ or } \log(\mathrm{Nu}) = \log(A_N) + \alpha \log(\mathrm{Re})$$

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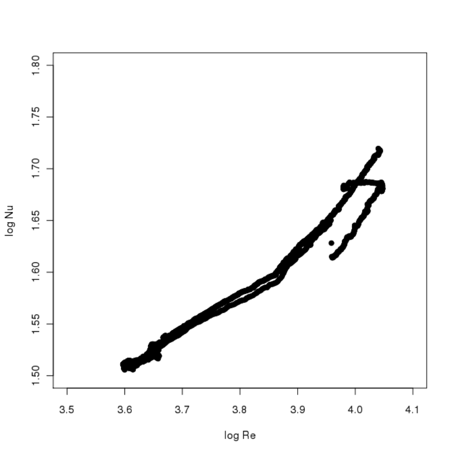
2. For the GV especially, dynamic heating increases the temperature of the air in thermal contact with the sensor, affecting the heat transfer from the wire.
3. Flow distortion around the wings and probes may cause size-dependent sorting of droplets with associated size-dependent increases or decreases in concentration.
4. Flow at an angle to the sensor will reduce the heat loss (approximately as the cosine of the flow angle relative to the axis of the sensing wire).

GV Data (PREDICT)

Examples

1. Data for a full flight (excluding low TAS)



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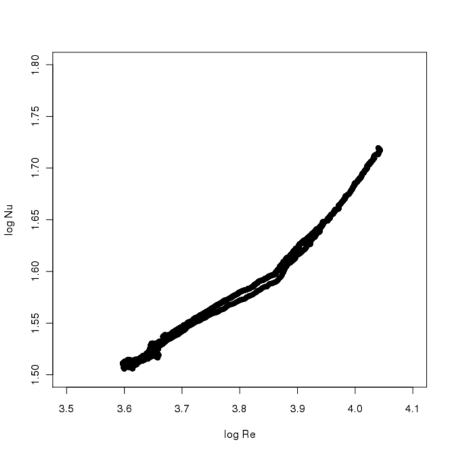
1. Data for a full flight (excluding low TAS)
2. Data excluding end of flight with flaps/gear



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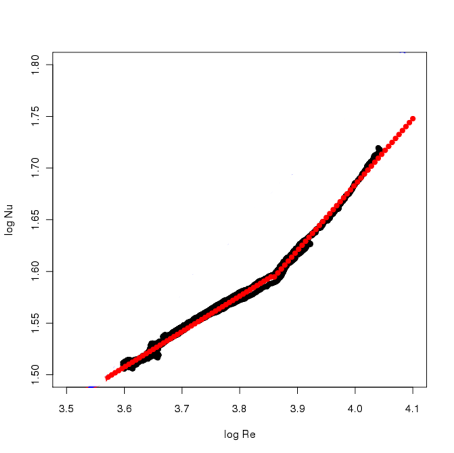

GV Data (PREDICT)

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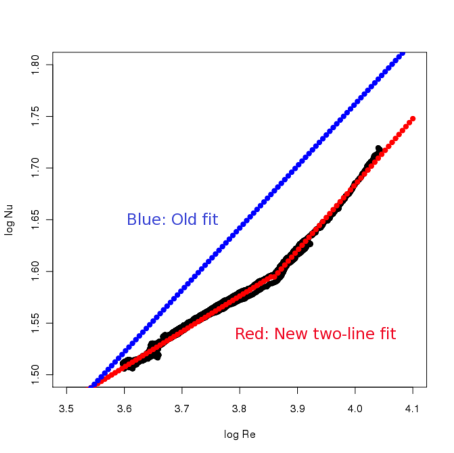
4. Comparison to current parameterization



What is the Vaporization Temperature?

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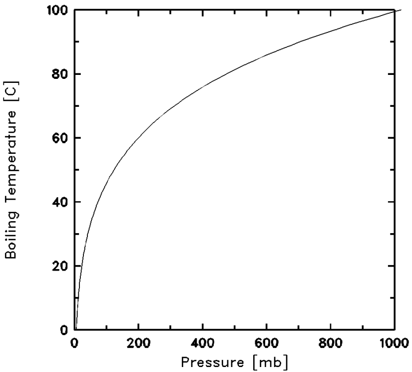
Temperature to use for T_w

- King et al. (1978) recommended $T_{shed} < T_w < T_{BP}$
- Wire temperature now 130–165°C
- T_{BP}: Reason for 100°C in equations
- However, the boiling point decreases with pressure:



Baseline Removal

Current Technique

1. When out-of-cloud:
   - calculate running-average LWC (30 s)
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Advantage (small)

If T and TAS vary in cloud:

- Updated Nu represents these variations via Re
- Updated zero does not

GV Results

PREDICT

1. PREDICT: hard to find real LWC regions
2. still can do calculations where CONCD>0.1
3. Result: Some compensating changes:
   - most important: $L_v(T)$ higher, $c_w T_{BP}$ lower
   - net change in example: about 4% increase, <0.002 RMS

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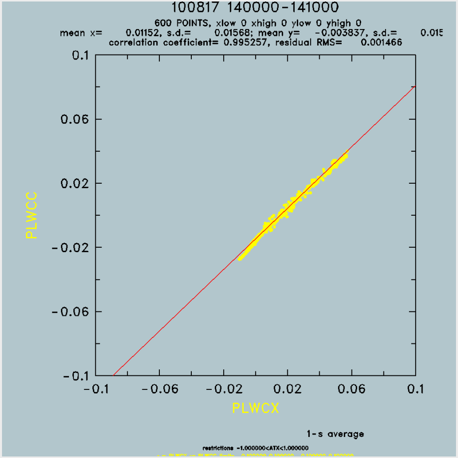

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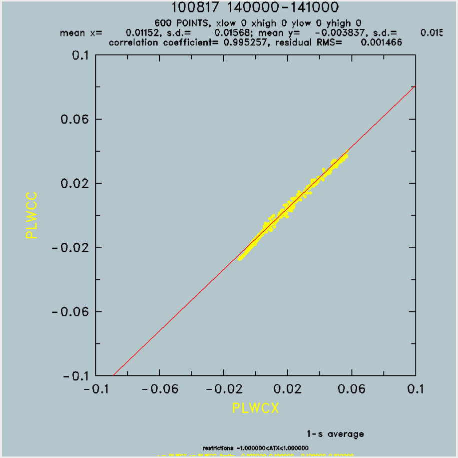
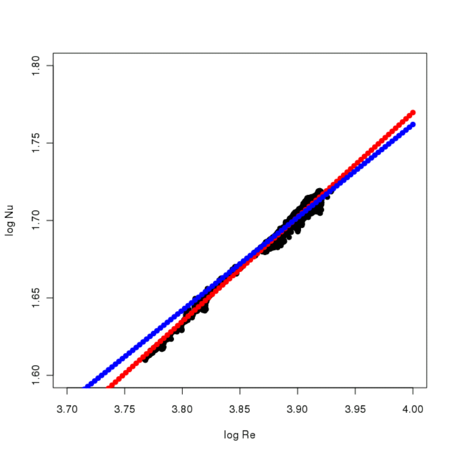


C130 Results

VOCALS

1. Determine Nu-Re relationship according to new scheme
   - new fit (red) is close to old curve (blue)
2. Result: changes are larger:
   - increase of about 9%, mostly from L_v change
   - some scatter arises from zero correction: $<0.01\,\mathrm{g\,m^{-3}}$.



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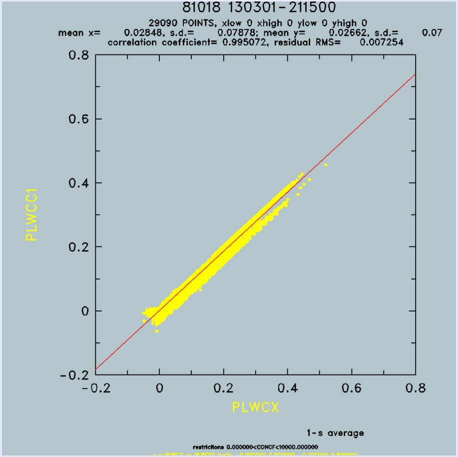

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8. Change the baseline correction to update the dry-air term.