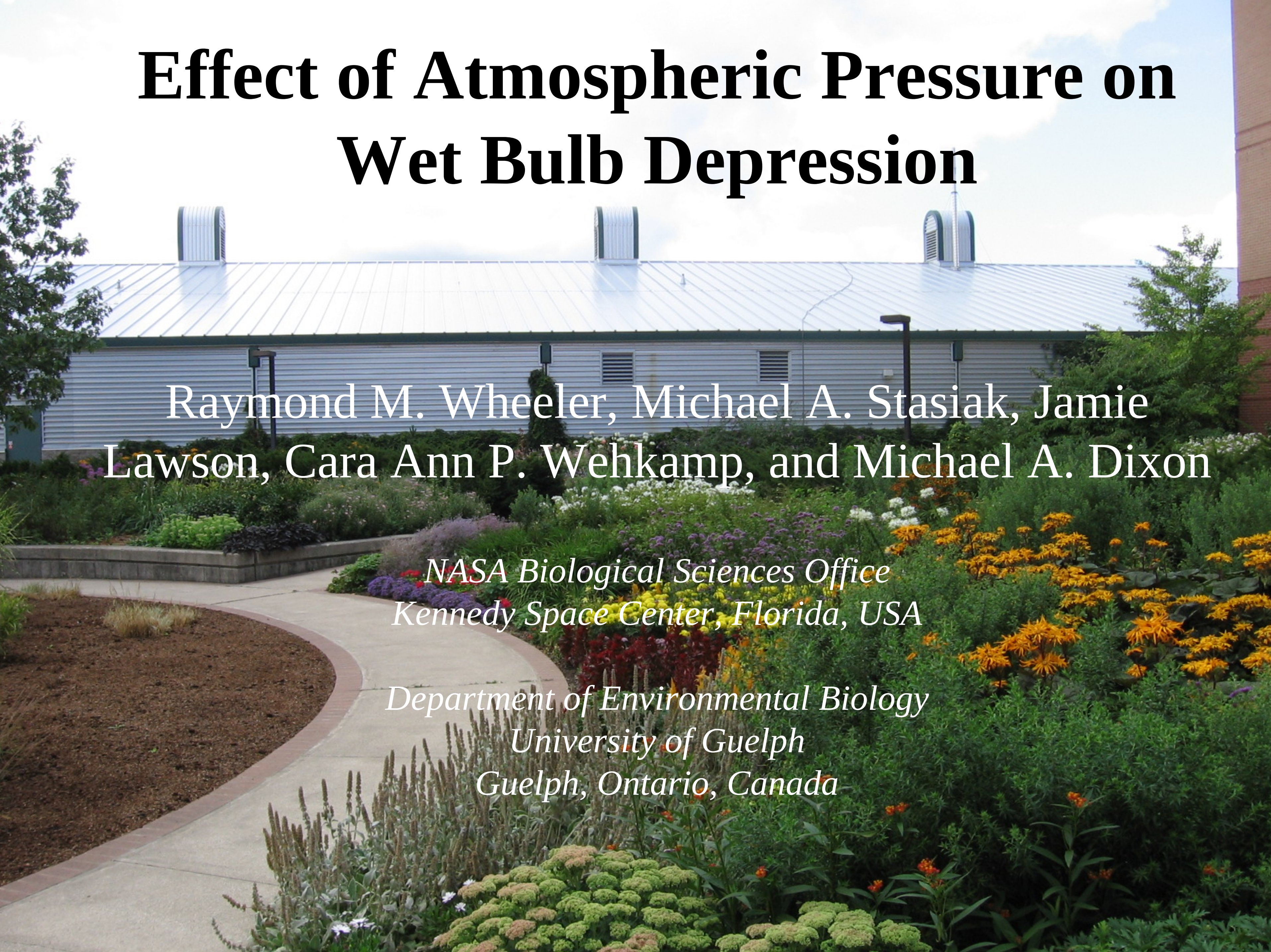
Effect of Atmospheric Pressure on Wet Bulb Depression



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Reduced Pressures for Space Missions?

- Reduced gas leakage and hence reduced resupply costs
- Reduced structural mass
- Increased potential for finding transparent materials for space “greenhouses”
- Rapid egress for EVAs (spacewalks) without prolonged prebreathing and acclimation

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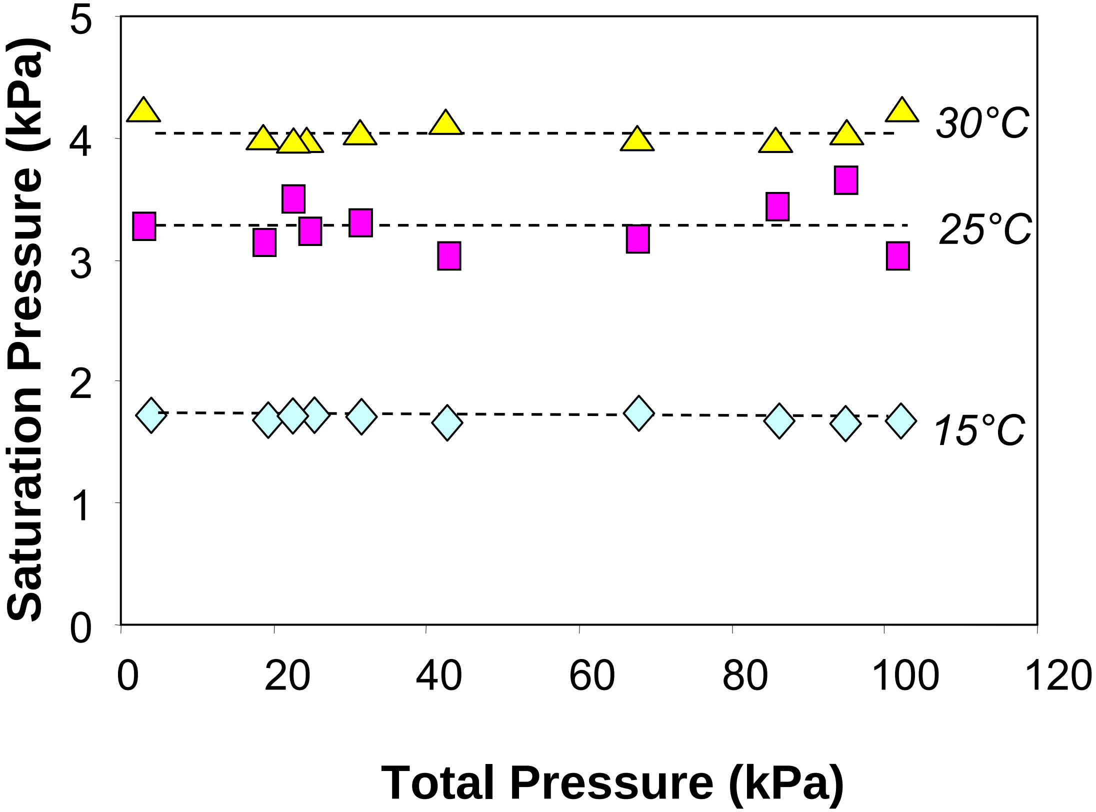
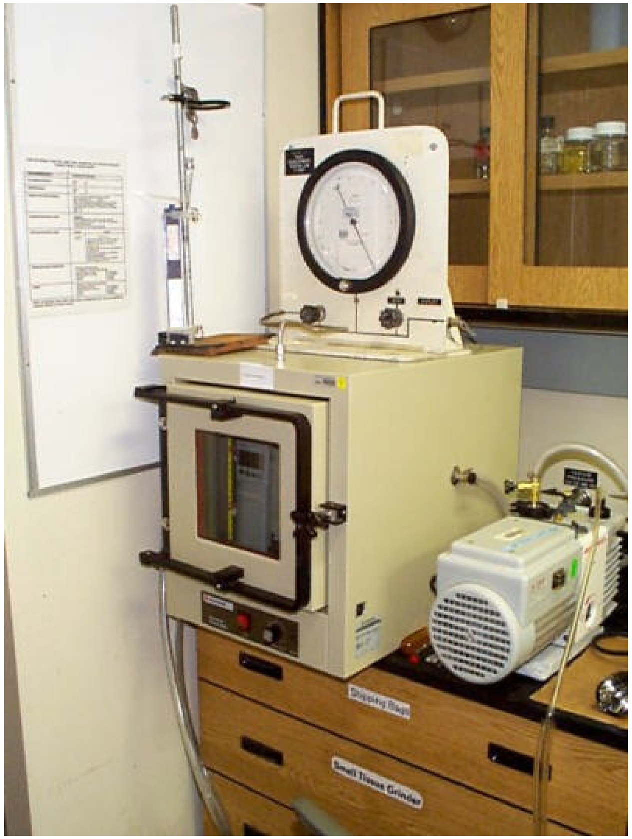
- How do environmental sensors perform at reduced pressures?

Effect of Pressure on Saturation Vapour Pressure

(Rygalov et al., 2004, *NASA Ken Space Center , FL*)





Steam table values for e_s: 30ºC = 4.24 kPa; 25ºC = 3.17 kPa; 15ºC = 1.70 kPa (Kennan, Keyes, et al., 1978)

Different Equations for Calculating Saturation Water Vapour Pressures

Goff-Gratch (1946) /
and Smithsonian Tables (1984)

$$
\begin{aligned}
\mathrm{Log}_{10}\, p_w = {} & -7.90298\ (373.16/T-1) \\
& + 5.02808\ \mathrm{Log}_{10}(373.16/T) \\
& - 1.3816\ 10^{-7}\ (10^{11.344\ (1-T/373.16)}\ -1) \\
& + 8.1328\ 10^{-3}\ (10^{-3.49149\ (373.16/T-1)}\ -1) \\
& + \mathrm{Log}_{10}(1013.246)
\end{aligned}
$$

with T in [K] and p_w in [hPa]

Hyland and Wexler (1983)

$$
\begin{aligned}
\mathrm{Log}\, p_w = {} & -0.58002206\ 10^{4} / \mathrm{T} \\
& + 0.13914993\ 10^{1} \\
& - 0.48640239\ 10^{-1}\ T \\
& + 0.41764768\ 10^{-4}\ T^{2} \\
& - 0.14452093\ 10^{-7}\ T^{3} \\
& + 0.65459673\ 10^{1}\ \mathrm{Log}(T)
\end{aligned}
$$

with T in [K] and p_w in [Pa]

Magnus Teten (Murray, 1967)

$\mathrm{Log10}\ p_w = 7.5\ t / (t+237.3) + 0.7858$

with t in [°C] and p_w in [hPa]

Buck (1981, 1996)

$p_w = 6.1121\ \ e(18.678 - t / 234.5)\ t / (257.14 + t)$

[1996] $p_w = 6.1121\ e17.502\ t / (240.97 + t)$

[1981] with t in [°C] and p_w in [hPa]

Sonntag (1994)

$$
\begin{aligned}
\mathrm{Log}\, p_w = {} & -6096.9385 / T \\
& + 16.635794 \\
& - 2.711193\ 10\text{-}2 * T \\
& + 1.673952\ 10\text{-}5 * T^{2} \\
& + 2.433502 * \mathrm{Log}(T)
\end{aligned}
$$

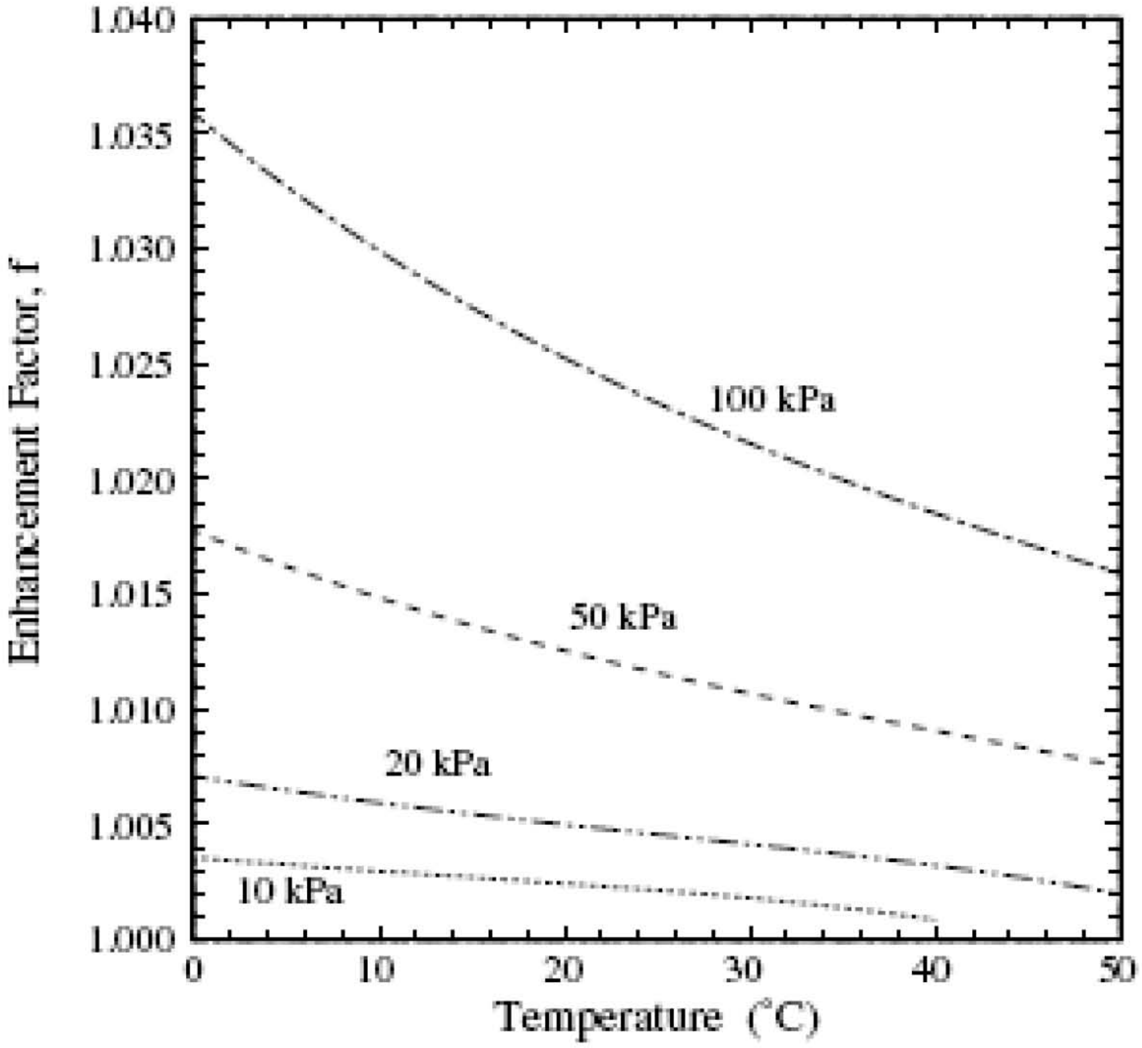
with T in [K] and p_w in [hPa]

→ All of these equations are related to saturation pressure of pure water vapour, but water vapour in air does not behave as a completely ideal gas and a corrections are required.

***Buck (1981) Equation*:**

$$e'_s = (f)\ 6.1121 \exp\left(\frac{17.502\ T}{240.97 + T}\right)$$

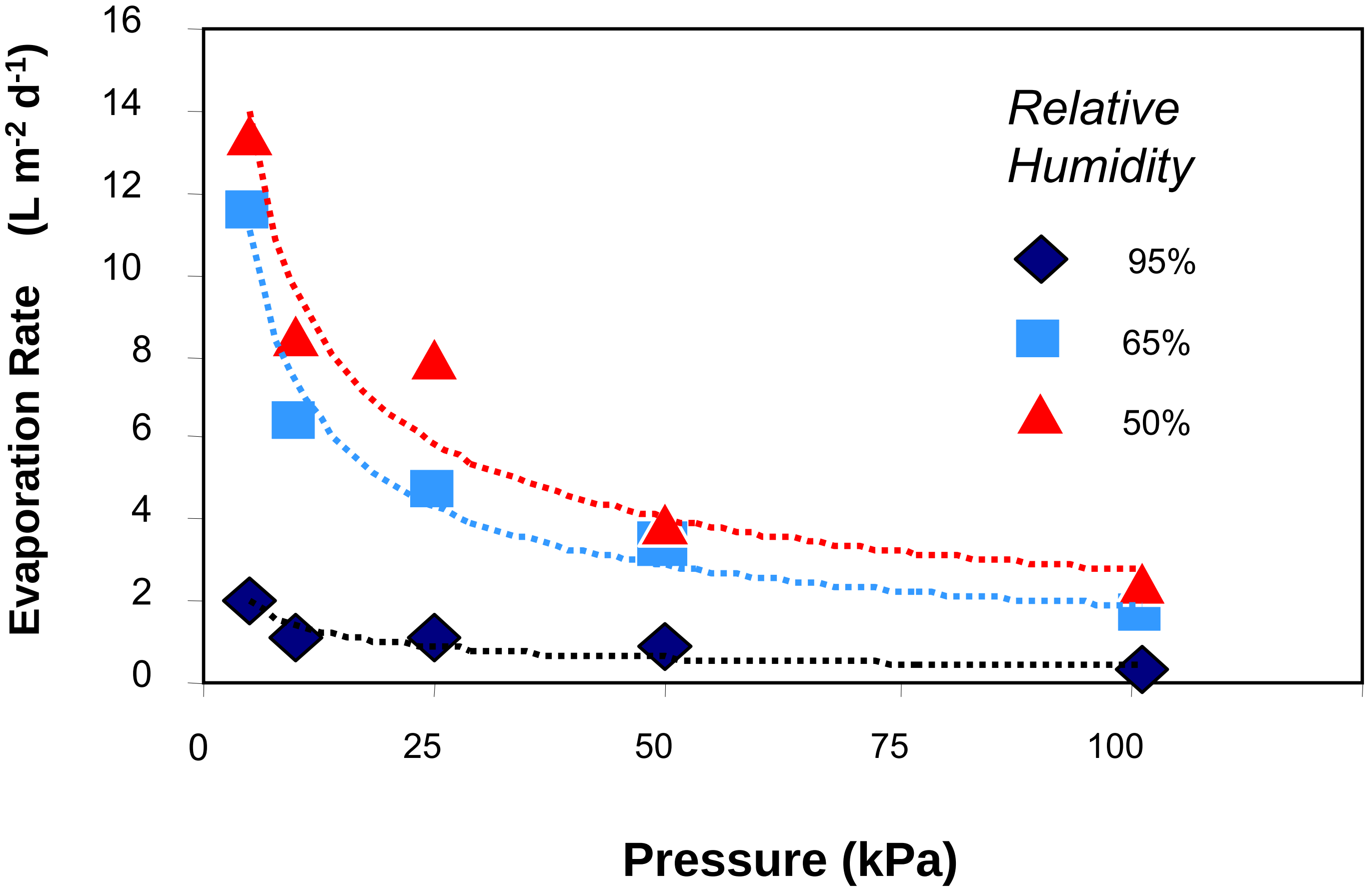
Where f = the "enhancement factor" for calculating vapor pressure of moist air instead of pure water vapor. Buck (1981) J. Appl. Meteorol. 20:1527-1532.



Effect of temperature and pressure on enhancement factor for correcting moist air properties to that of pure water vapor. *From: D.C. Shallcross. 2005. Intl. J. Heat and Mass Transfer 48:1785-1796.*

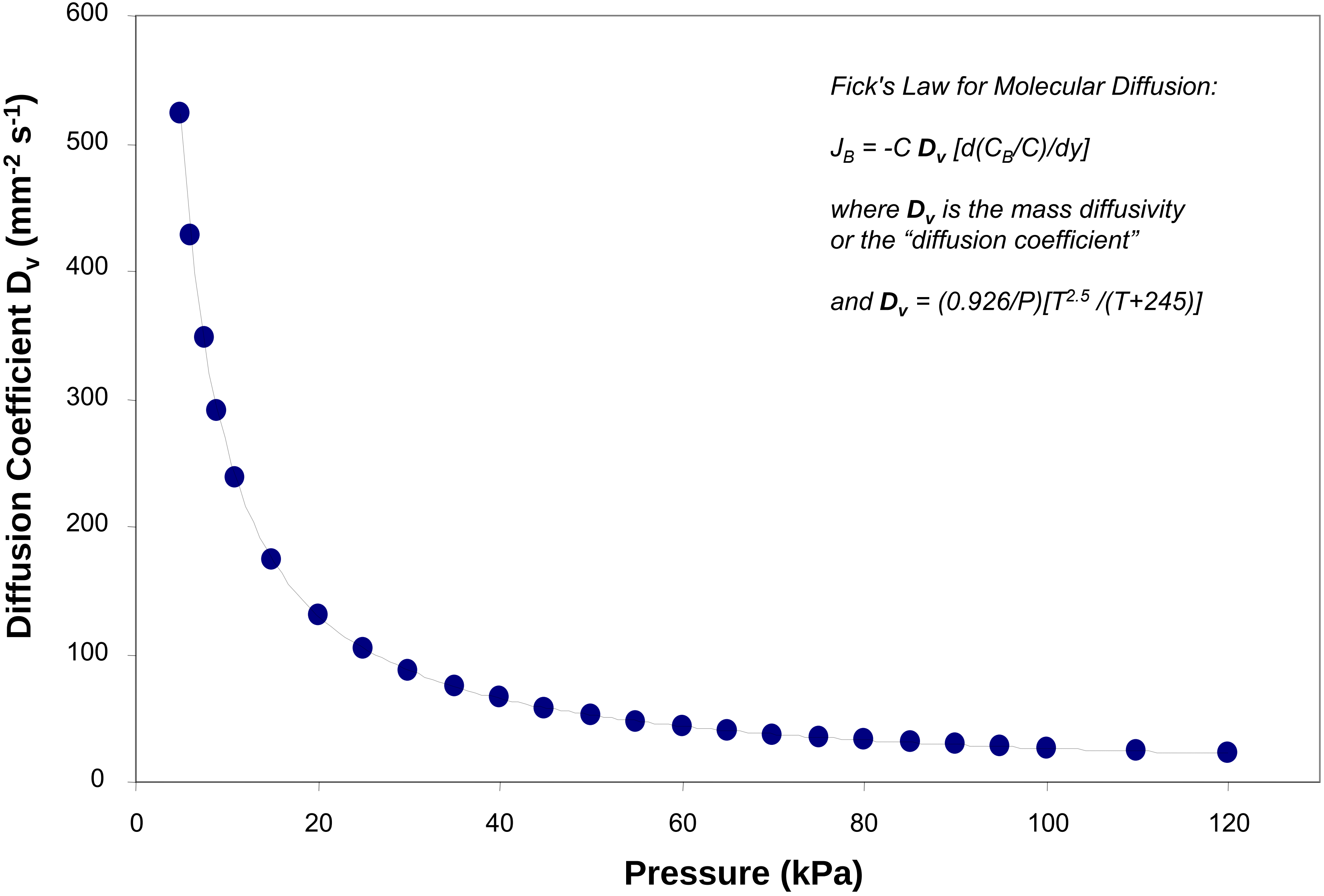
Effects of Pressure on Evaporation Rates

(Rygalov et al., 2004)



→ *Related to increased gas diffusion rates at reduced pressures*

Diffusion Coefficient (D_v) of Water Vapour at 25ºC



Fick's Law for Molecular Diffusion:

$J_B = -C\,\mathbf{D_v}\,[d(C_B/C)/dy]$

where $\mathbf{D_v}$ *is the mass diffusivity*
or the "diffusion coefficient"

and $\mathbf{D_v} = (0.926/P)[T^{2.5}/(T+245)]$

If evaporation rates increase at reduced pressures…..

then wet-bulb (WB) depression should also increase.

Psychrometric Equation

using Wet Bulb Temperature

$$e_s' = e + \gamma\,(T_{db} - T_{wb})$$

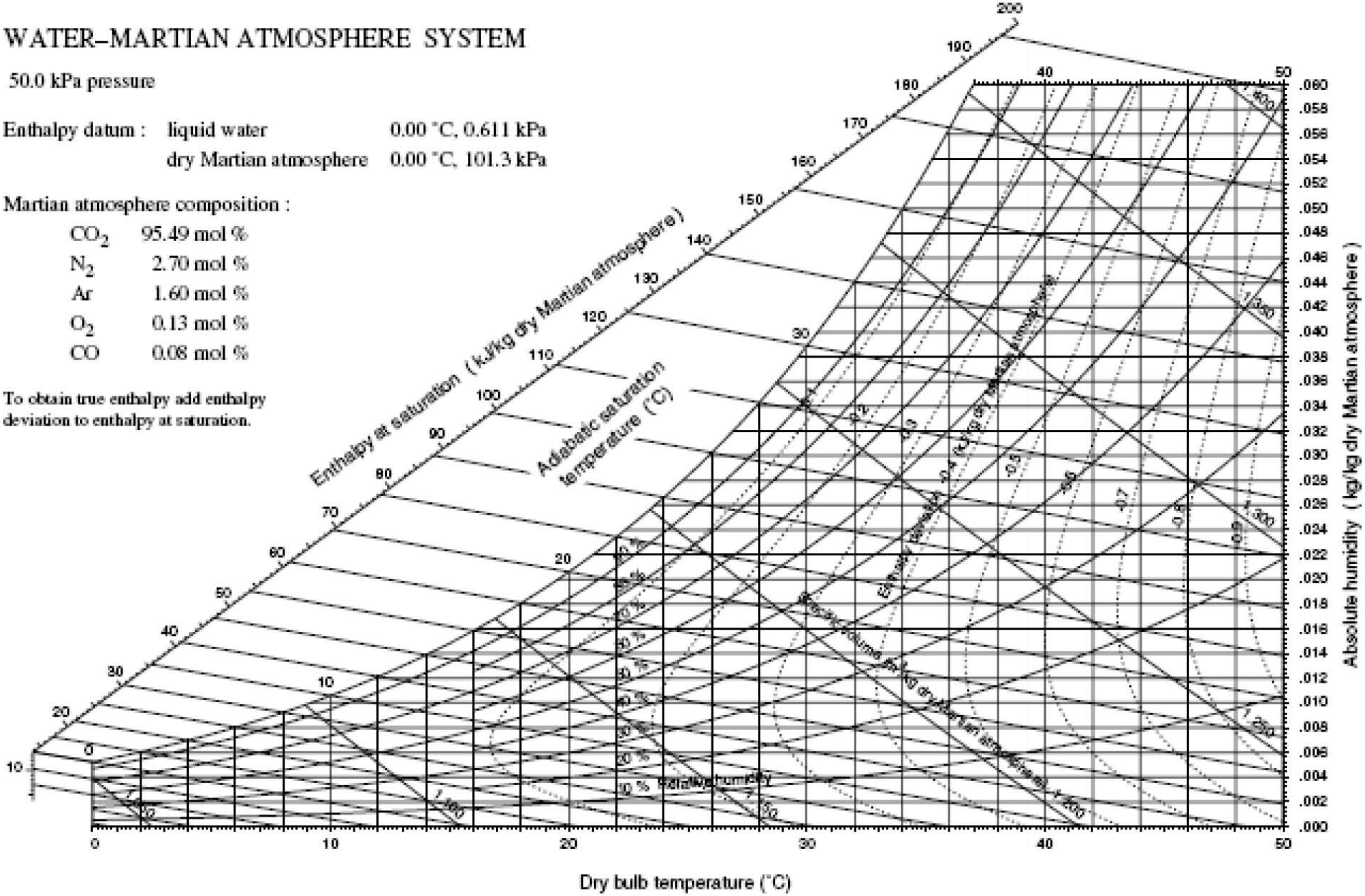
γ = *the psychrometric constant*

where $\gamma = p\,A$

with p *= pressure and* $A \approx 6.53 \times 10^{-4}\ K^{-1}$ *for average size thermometers and aspiration rate of* $4\ m\ s^{-1}$

But e_s' ***is saturation vapour pressure at the wet bulb temperature !***

Thus this equation can't be used the to solve directly for T_{wb} ***.***



WATER–MARTIAN ATMOSPHERE SYSTEM

50.0 kPa pressure

Enthalpy datum :	liquid water	0.00 °C, 0.611 kPa
	dry Martian atmosphere	0.00 °C, 101.3 kPa

Martian atmosphere composition :

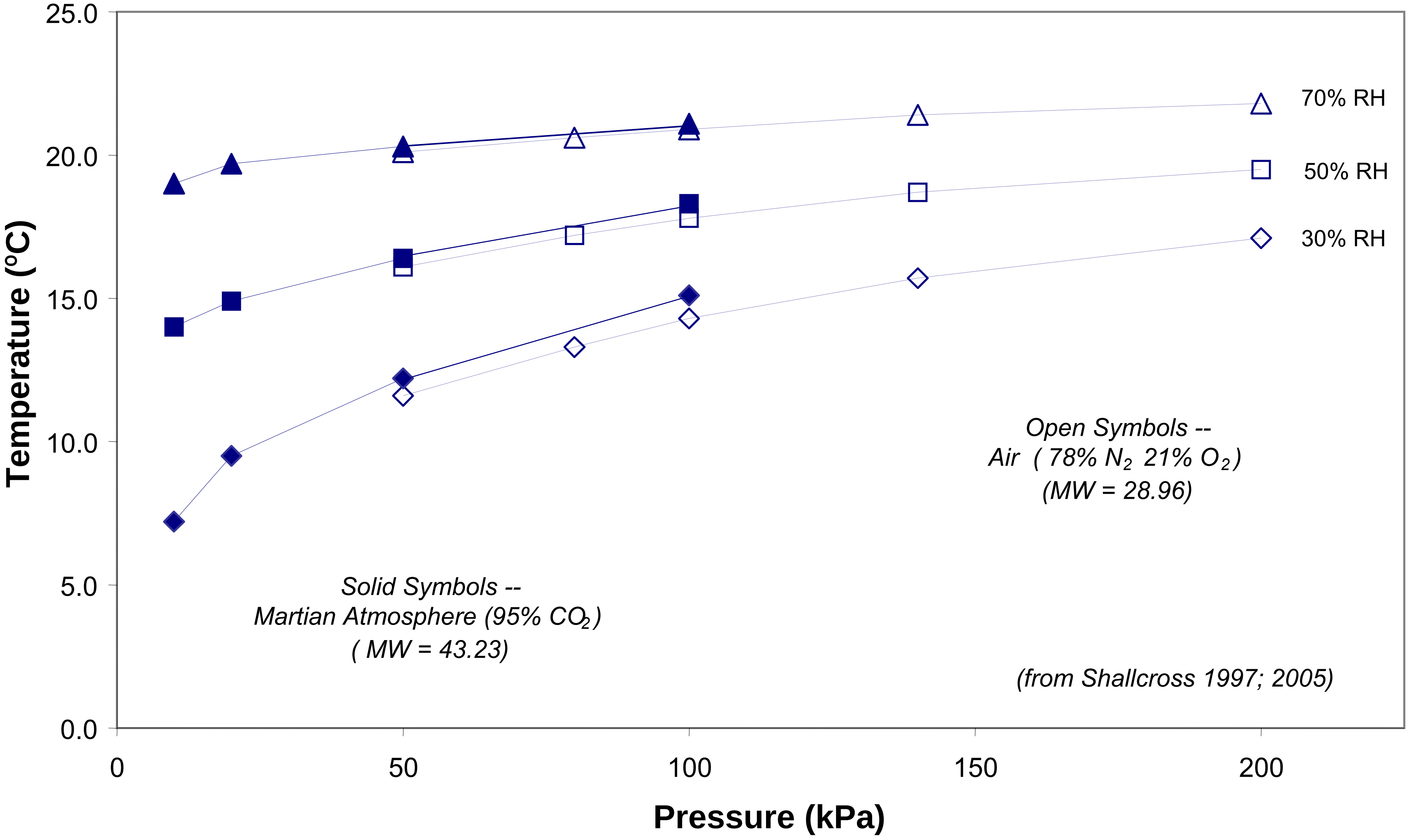
CO_2	95.49 mol %
N_2	2.70 mol %
Ar	1.60 mol %
O_2	0.13 mol %
CO	0.08 mol %

To obtain true enthalpy add enthalpy deviation to enthalpy at saturation.

Psychometric chart for water vapor in Martian atmosphere brought to 50 kPa pressure.
From: D.C. Shallcross. 2005. Intl. J. Heat and Mass Transfer 48:1785-1796.

Themodynamic Wet Bulb Temperature vs. Pressure

(at 25°C Dry Bulb in Air and Martian Atmosphere)

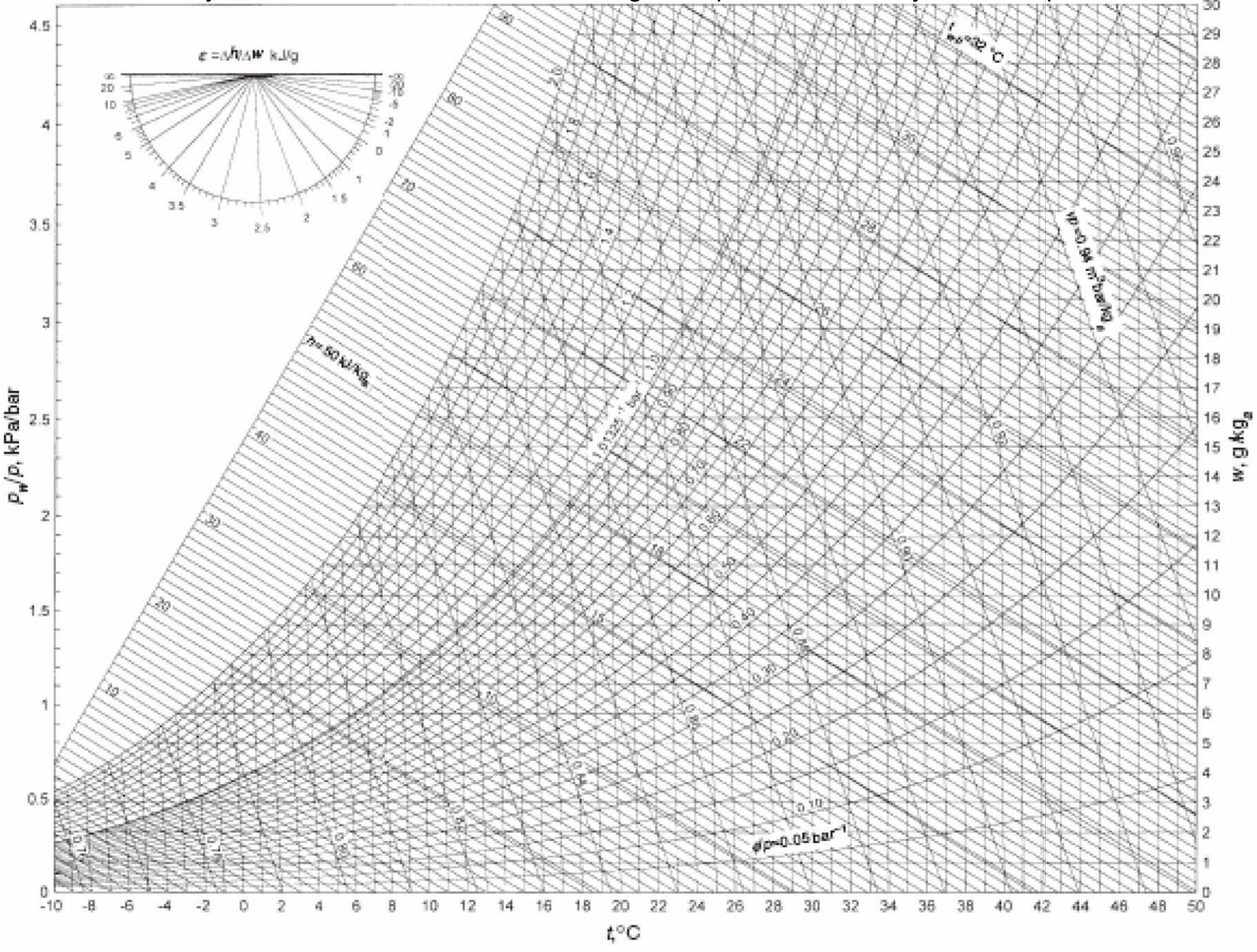


Open Symbols --
Air (78% N_2 21% O_2)
(MW = 28.96)

Solid Symbols --
Martian Atmosphere (95% CO_2)
(MW = 43.23)

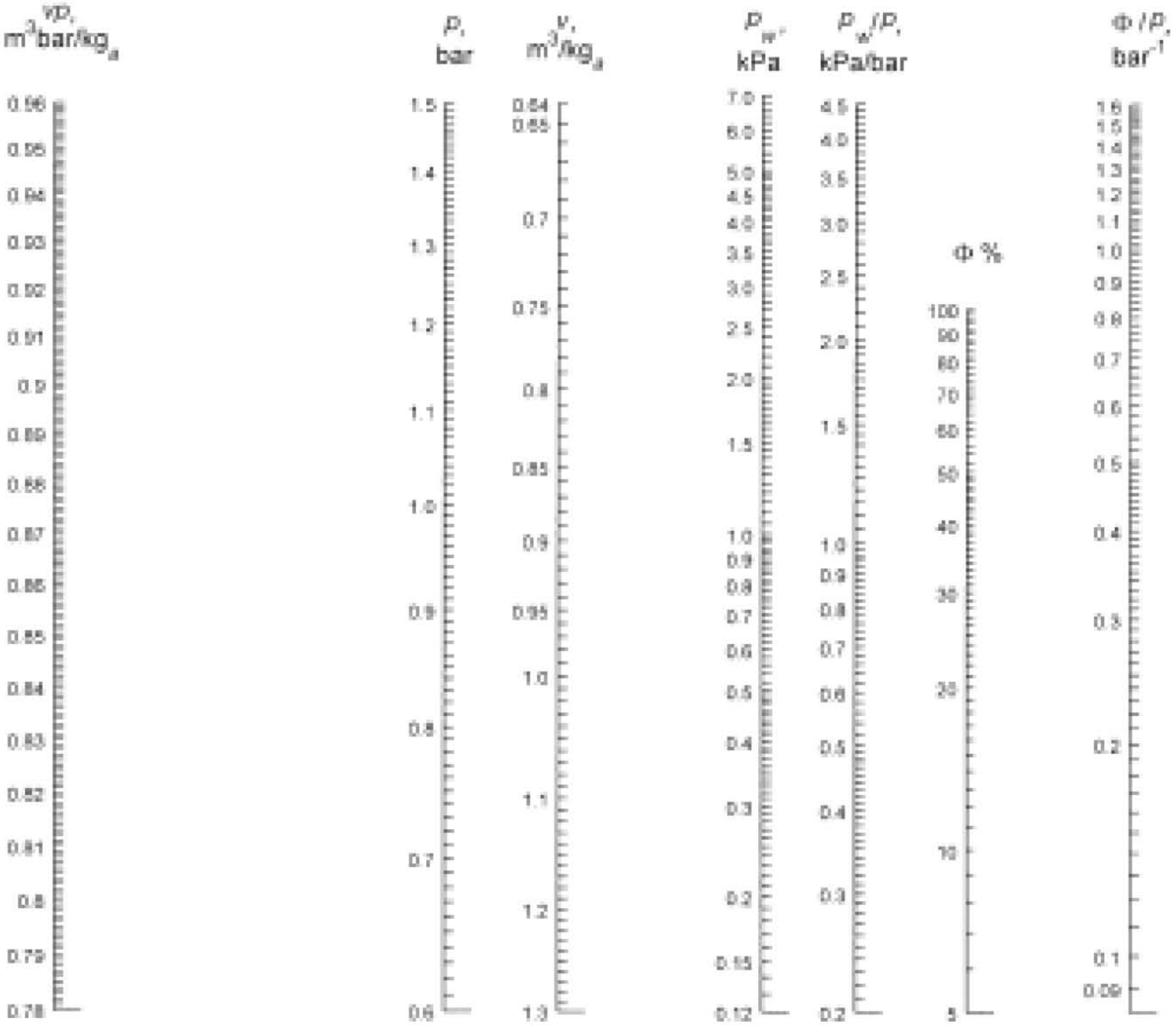
(from Shallcross 1997; 2005)

Psychrometric Chart for Pressure using “Composite” Thermodynamic Properties



H.-S. Ren. 2004. Construction of a generalized psychrometric chart for different pressures. J. Mech. Eng. Ed. 32(3):212-222.

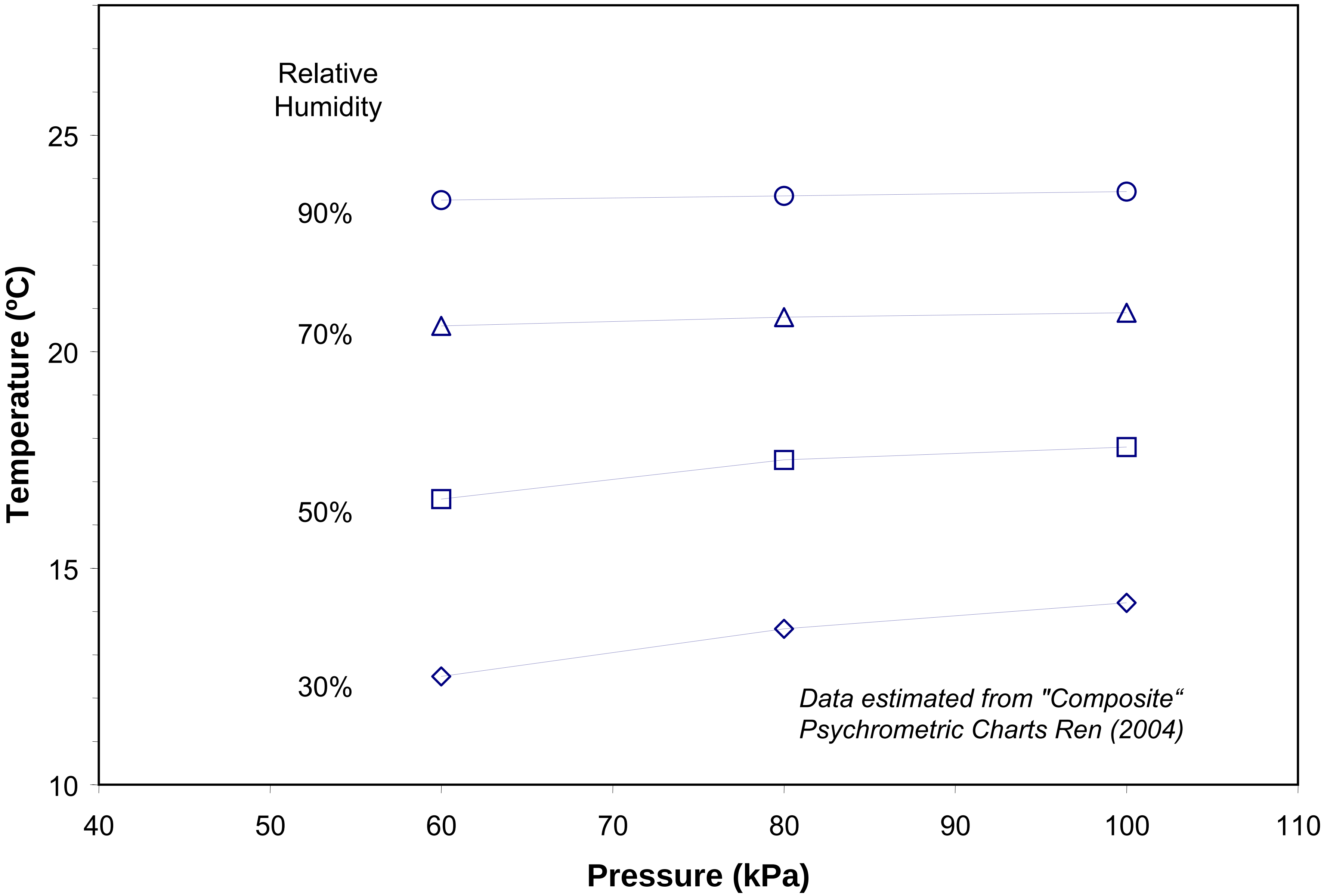
Composite Psychrometric Chart Nomograph



H.-S. Ren. 2004. Construction of a generalized psychrometric chart for different pressures. J. Mech. Eng. Ed. 32(3):212-222.

Thermodynamic Wet Bulb Temperature vs. Pressure

(at Dry Bulb of 25ºC)



Data estimated from "Composite“ Psychrometric Charts Ren (2004)

→ Our objective was to directly measure wet bulb depression at different pressures and compare our results published psychrometric models for pressure effects.

Experimental Approach

- Measure wet bulb temperatures five different pressures and three different relative humidities:
  - Pressures: 10, 20, 50, 80, and 100 kPa
  - Relative Humidities: 30, 50, and 70%

  Each combination allowed to equilibrate for at least 90 minutes, then a 30-min segment of data was averaged for WB, DB, Dew Point, Chamber Air Temperature, Chamber RH, and Water Temperature

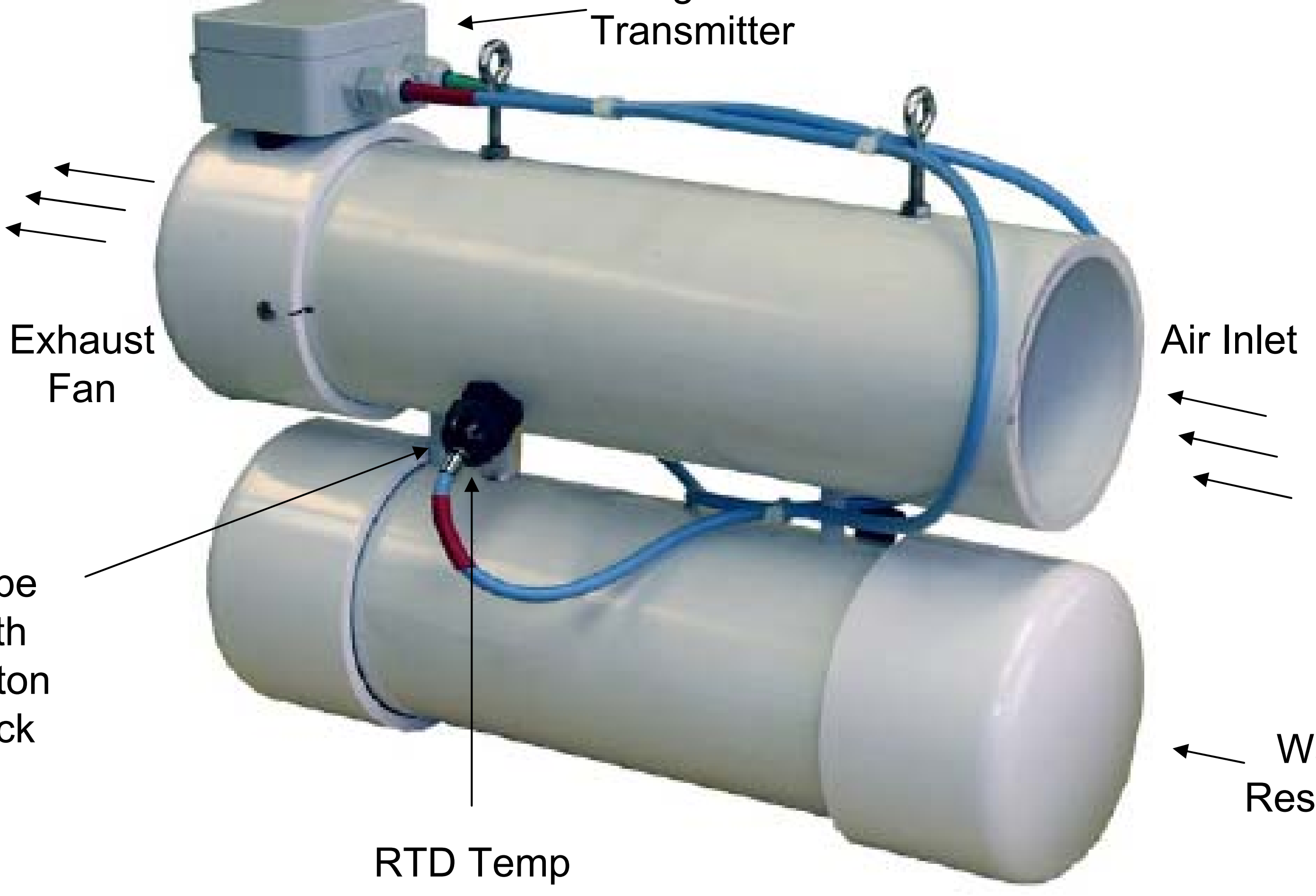
Hypobaric Test Chamber
University of Guelph, CESF

Environmental Monitoring and Control:

- Wet Bulb / Dry Bulb
  - Enercorp Model HT-WD-A Psychrometer
    - Two matched platinum RTD temperature probes
    - Constant aspiration -- 3 m s^{-1}
- Humidity Control
  - Honeywell Model HIH-3602-A Capacitance Sensors (2)
- Temperature Control
  - Argus TN 21 Thermisters (2)
- Dew Point Measurements
  - General Eastern Model 1100DP (1)
- Humidity Calibration / Comparison *(at 100 kPa)*
  - Vaisala HMP42 Handheld RH/Temp Probe
- Pressure Monitoring / Control
  - MKS 'Barotron' Capacitance Manometer
- Water temperature for the psychrometer reservoir

Wet / Dry Psychrometer

Enercorp Inst. Ltd. (Model HT-WD-A)



Signal Transmitter

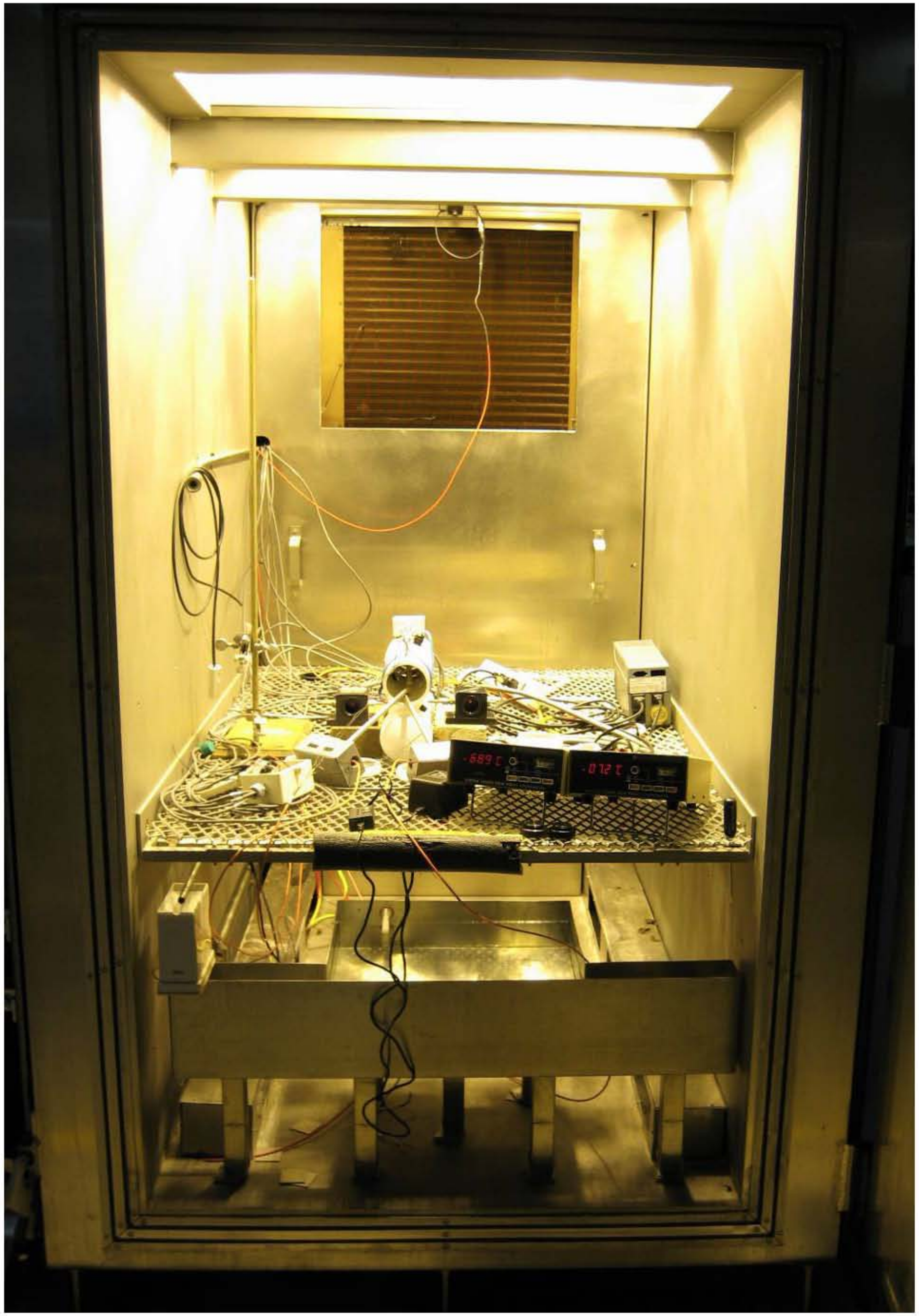
Exhaust Fan

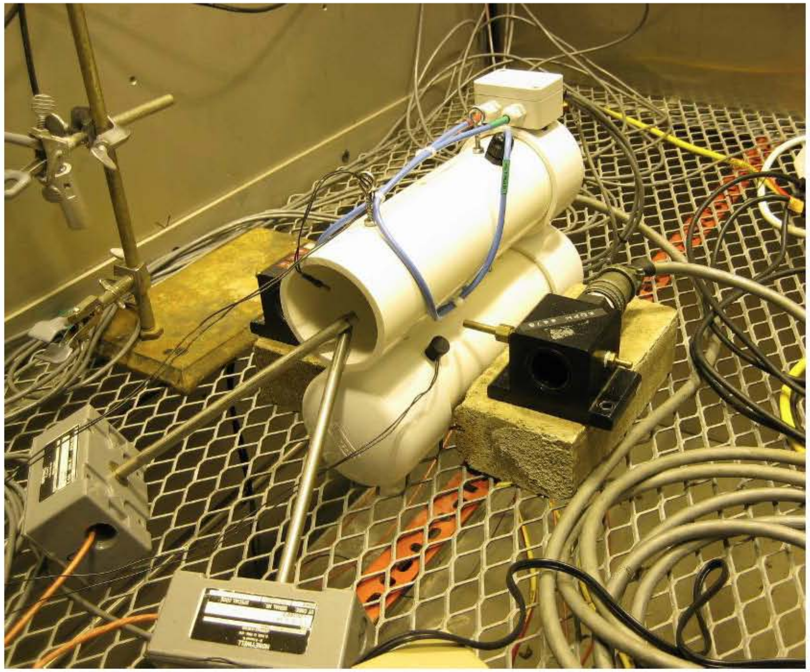
Air Inlet

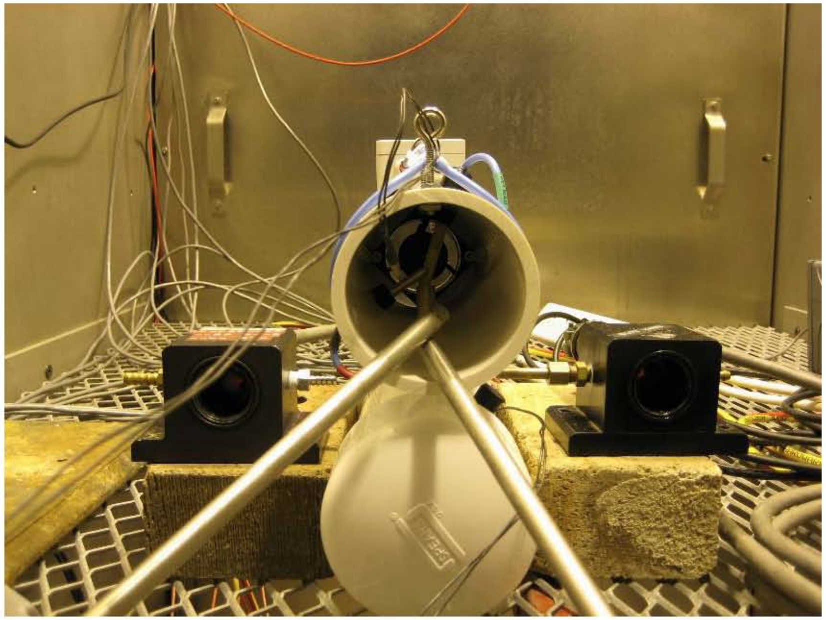
Tube with Cotton Wick

Water Reservoir

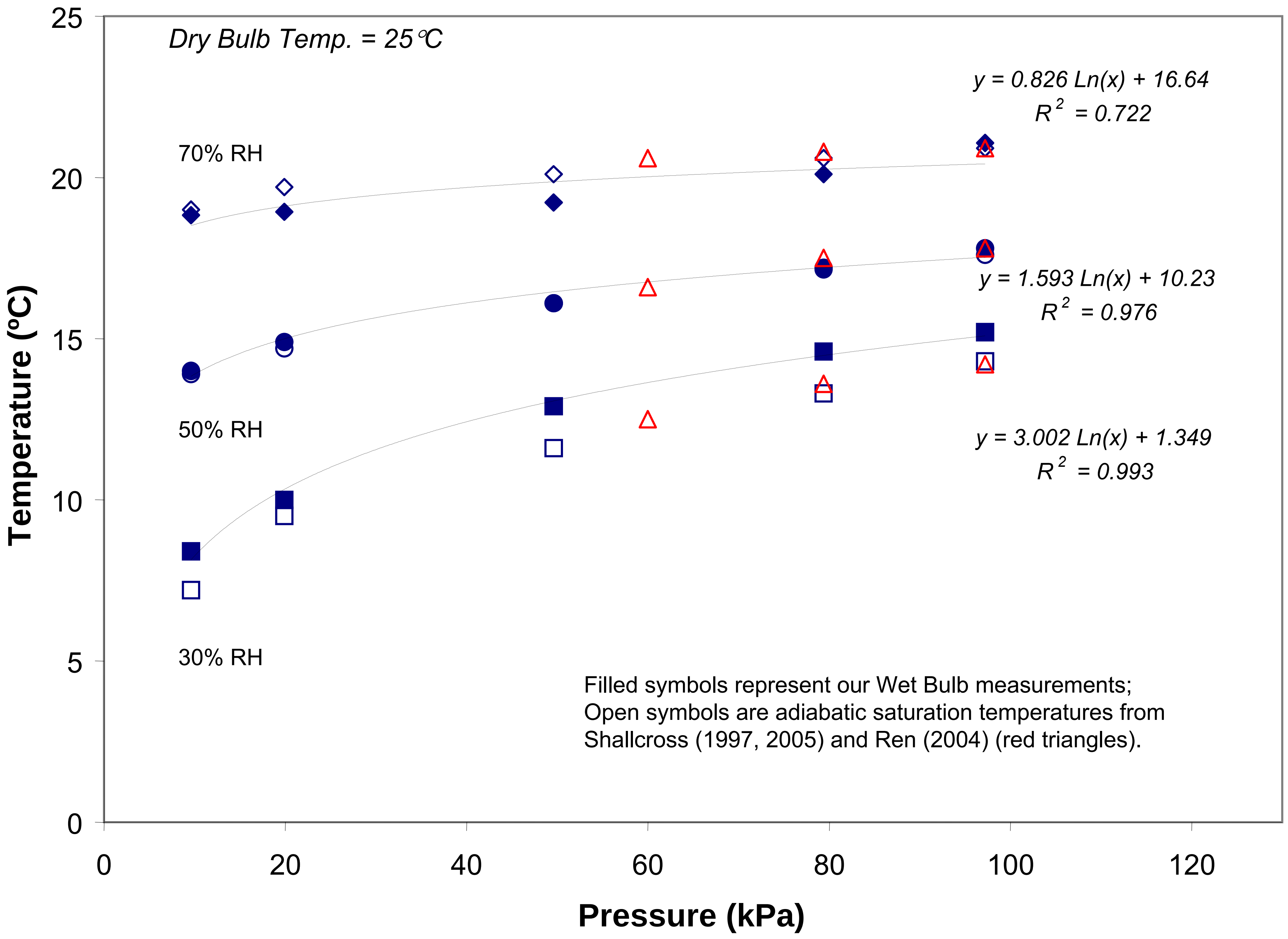
RTD Temp Probe


-689 C
-072 C





Wet Bulb Measurements versus Atmospheric Pressure



Filled symbols represent our Wet Bulb measurements;
Open symbols are adiabatic saturation temperatures from
Shallcross (1997, 2005) and Ren (2004) (red triangles).

Conclusions

- Our measurements of wet bulb depression at different pressures matched the modeled adiabatic saturation temps reasonably well.
- At a dry bulb temp of 25°C, the normal wet bulb temp for 30% RH and 100 kPa is ~15°C, but this dropped to ~8°C at 10 kPa.
- The results suggest that psychrometers need direct calibration at the target pressures or that pressure corrected charts are required.
- For a given vapour pressure deficit, any moist surfaces, including transpiring plant leaves, will be cooler at lower pressures due to the increased evaporation rates.

Thanks
to the
CESRF
Team at
University
of Guelph

Mike Stasiak

Jamie Lawson

Questions ?

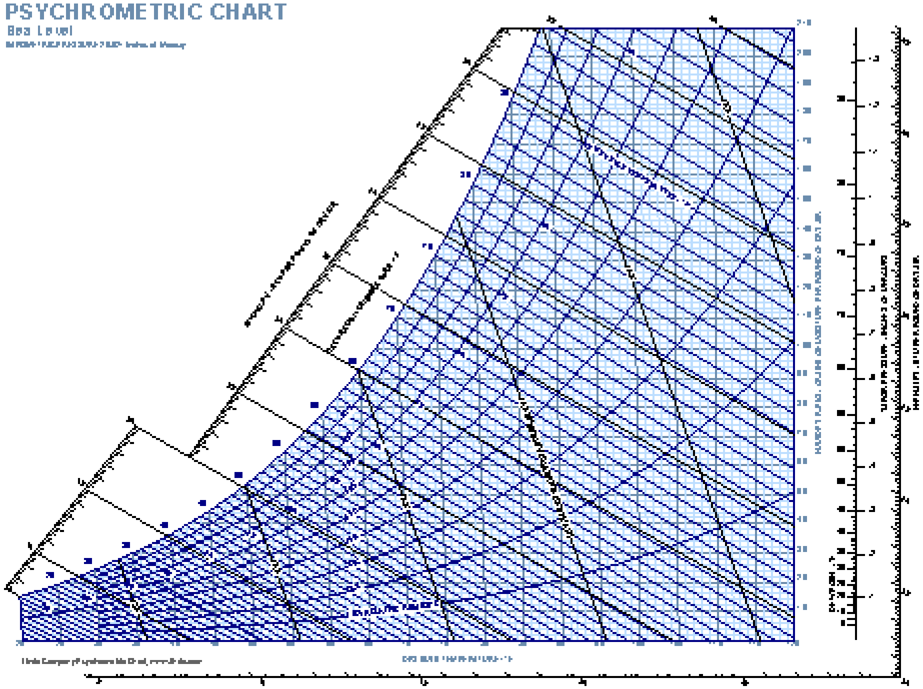
Welcome to Florida !

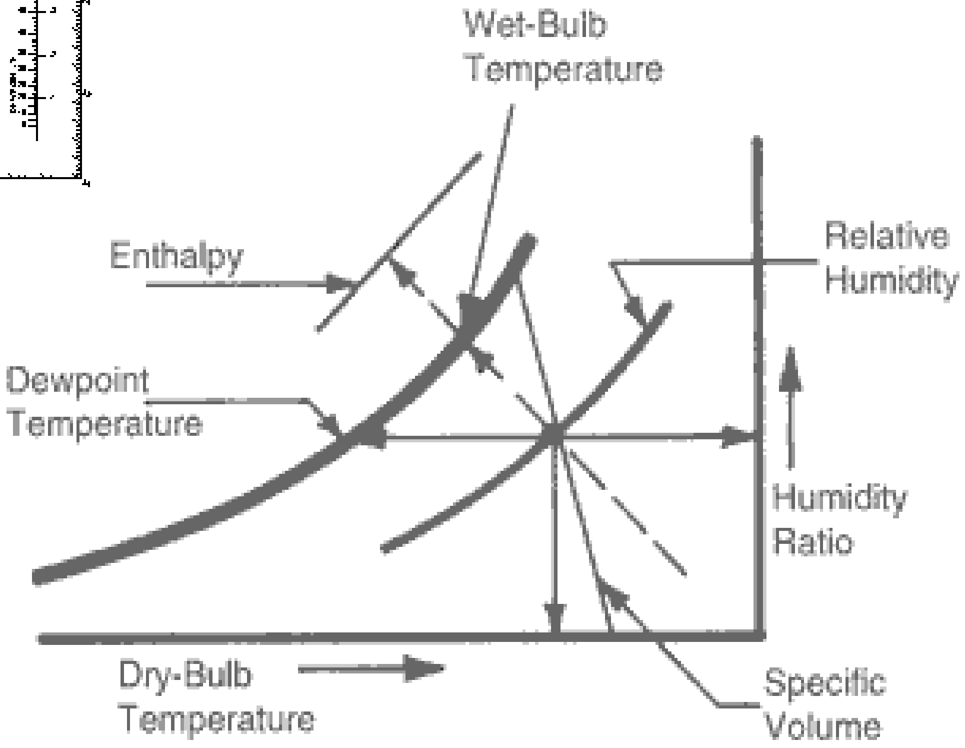
Wet Bulb Temperature vs. Adiabatic Saturation Temperature

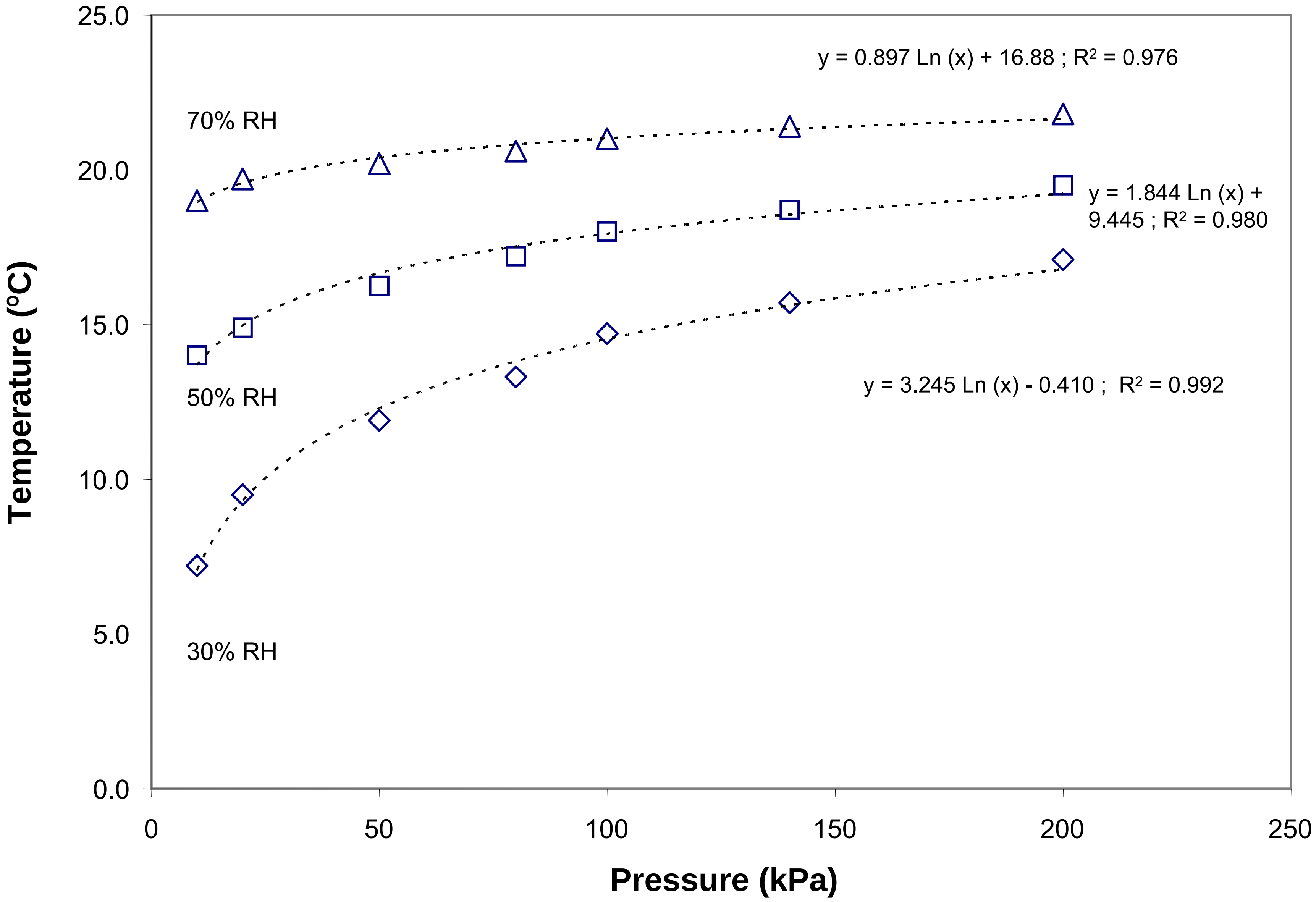
Wet Bulb Temperature: The temperature of a sensor covered with pure water that is evaporating freely into the ambient air stream. Typically taken with a “matched” dry bulb (DB) reading under constant aspiration (3-5 m s^{-1}) and shielded from radiation. But WB readings can be affected by the aspiration rate, mass of the sensor, water temperature, properties of the wick, and water purity.

Adiabatic Saturation Temperature (also called Thermodynamic Wet Bulb Temperature): The thermodynamic state resulting from adiabatic saturation, where there is no heat or mass transfer involved, and is independent of the measurement technique.

The Psychrometric Chart







Averaged* Chart of Dynamic WB Temperature vs. Pressure

Data for 12 and 20 kPa for CO_2 (95%) atmosphere; 80, 140, and 200 kPa for air; 50 and 100 averaged for CO_2 and air (Shallcross, 1997).