MATHEMATICAL ANALYSIS OF ASTM-96 BASED TEWL CALIBRATION METHOD

R E Imhof [1,2], M E P de Jesus [3], P Xiao [1,2] and the TEWL Calibration Consortium [4]

[1] Photophysics Research Centre, London South Bank University, London SE1 0AA, UK

[2] Biox Systems Ltd, Southwark Campus, 103 Borough Road, London SE1 0AA, UK

[3] Departamento de Fisica, Universidade da Beira Interior, 6200 Covilhã, Portugal

[4] The TEWL Calibration Project is sponsored by the UK Department of Trade and Industry. Project partners are:- EnviroDerm Services (project manager) (C L Packham and H E Packham), London South Bank University (R E Imhof, H E Packham and P Xiao), UK National Physical Laboratory (S A Bell, R M Gee and M Stevens), Biox Systems Ltd (E P Berg, R E Imhof and P Xiao), Dstl Porton Down (R P Chilcott & C H Dalton), and Gillette UK (A Stevens & N Weston)

Presentation Outline

Water Vapour Flux Density Calibration Methods

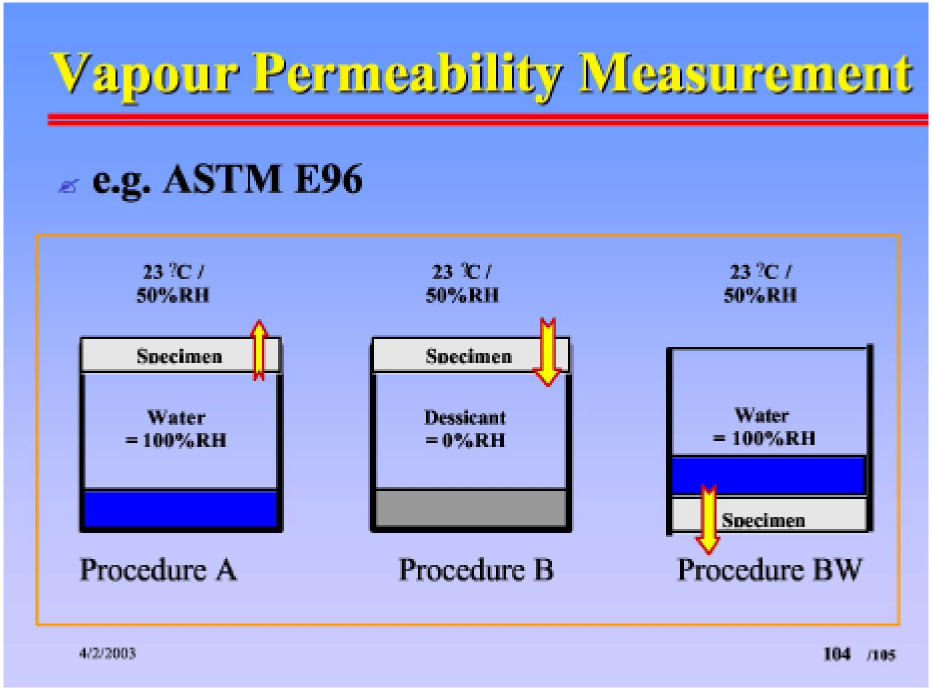
1. Membrane Methods

Widely used. Broadly based on the ASTM-96 standard.

2. Water Droplet Method

New approach, adopted when we discovered fundamental problems with the Membrane Method.

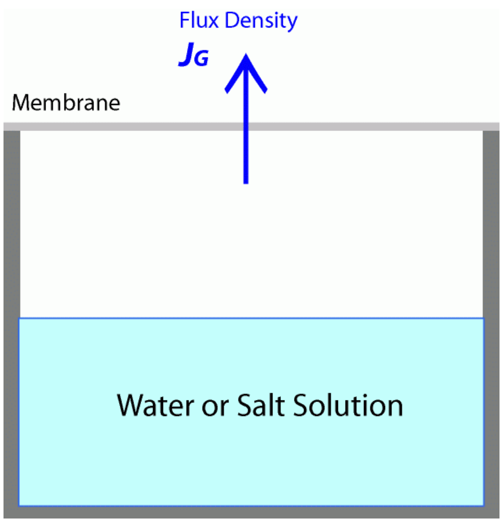
ASTM-96 Summary



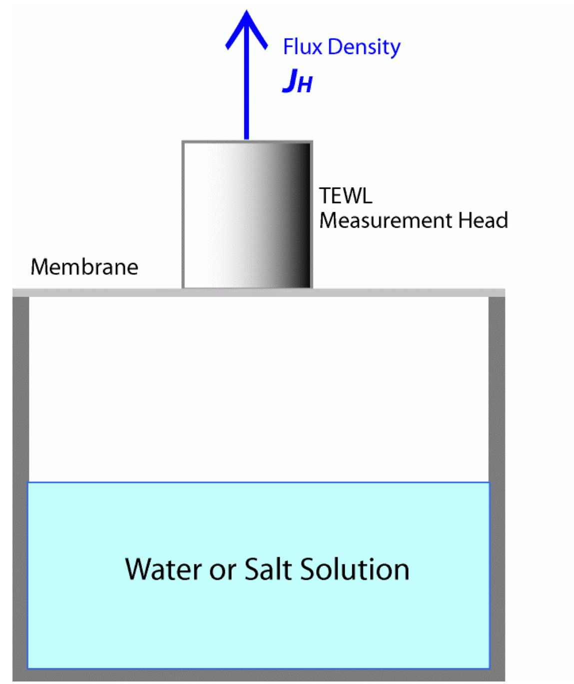
Reproduced from:- *Understanding Water: The Physics of Moisture Dynamics*. J Straube, University of Waterloo, Canada.

NB:- ASTM-96 was developed for characterizing membranes, NOT for calibrating TEWL.

Membrane Method for TEWL Calibration



Gravimetric measurement of Flux Density J_G, from cup weight loss

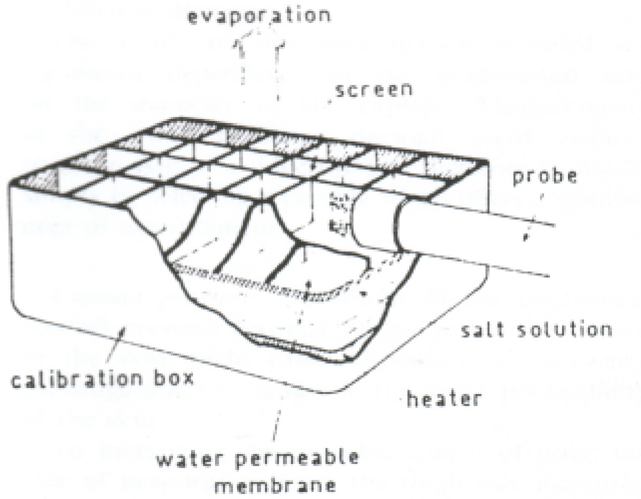


Calibration of TEWL instrument, assuming $J_H = J_G$

Membrane TEWL Calibration - Example 1

Flux calibrated from weight loss of saturated salt solution.

Reservoir covered by a permeable membrane.



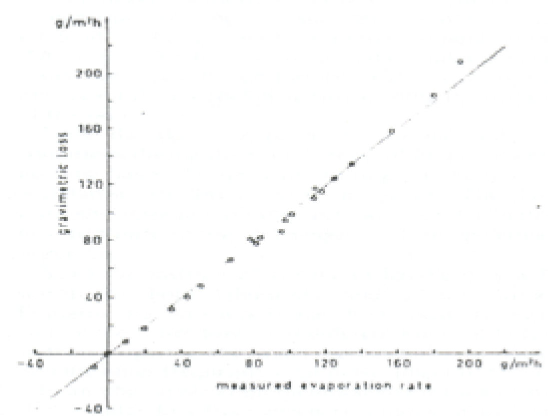


Fig. 12 Correlation between gravimetric loss and measured evaporation rate

Reproduced from:- *Measurement of Water Exchange through Skin*. G E Nilsson, Med Biol Comput, 15, 209-18, 1977.

Membrane TEWL Calibration - Example 2

Petri dish with Opsite membrane

Water temperatures 22-30 ºC (up to 80 ºC for linearity check)

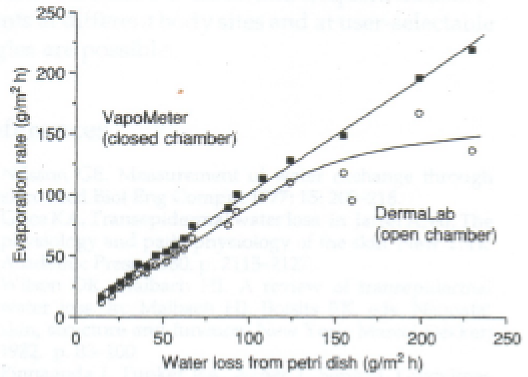


Fig. 3. Evaporation rate using a closed chamber (■) and an open chamber (○) evaporimeter (DermaLab®, Cortex Technology, Hadsund, Denmark) vs water loss from the petri dish per unit surface area and time.

Reproduced from:- *A Closed Unventilated Chamber for the Measurement of Transepidermal Water Loss.*
J Nuutinen, E Alanen, P Autio, M-R Lahtinen, I Harvima & T Lahtinen, Skin Res & Technol, 9, 85-9, 2003.

Membrane TEWL Calibration Model

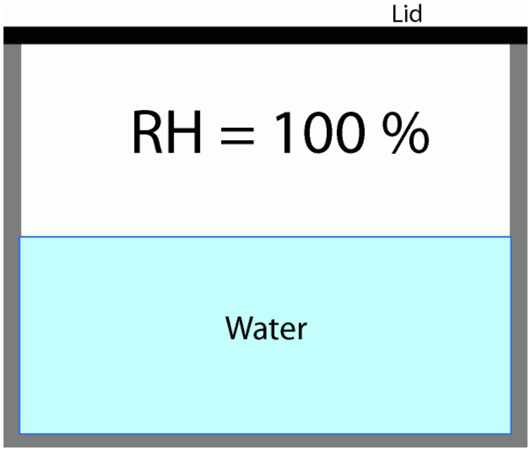
1. Closed Cup Vapour/Liquid Equilibrium

Consider a closed cup containing some water:-

For equilibrium, the temperature is uniform everywhere.

For equilibrium, the Relative Humidity (**RH**) of the enclosed air is 100%.

The model uses Vapour Density (Absolute Humidity, Vapour Concentration).



Note:-
Even in equilibrium at 100% RH, liquid water is **much more dense** than water vapour. Eg at 22ºC:-

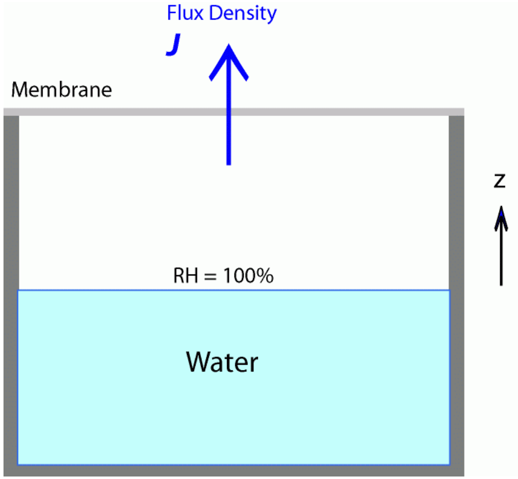
Water Vapour Density	$\rho_V \sim 0.02$ kg/m^3
Liquid Water Density	$\rho_L \sim 1000$ kg/m^3

$$\therefore \frac{r_V}{r_L} \approx \frac{1}{50000}$$

Membrane TEWL Calibration Model

2. Leaky Cup Vapour/Liquid Steady-state

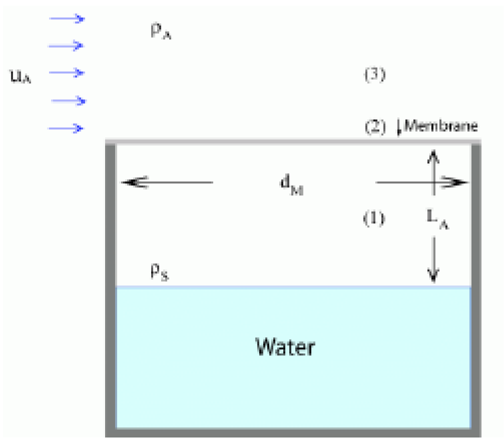
With a permeable lid, there is a flux of water vapour escaping into the ambient air. You no longer have equilibrium, but there can be a steady-state solution, where the flux ***J*** is constant. The RH at the water surface is still 100%, but the humidity falls off towards ambient RH as you move up and away from the water surface.



The question is - how to calculate ***J***.

Membrane TEWL Calibration Model

3. Flux Calculation for Leaky Cup



Divide the system into three regions:-

Region 1 (Below the Membrane)
Diffusion in air, ie Fick's law.

Region 2 (Within the Membrane)
Diffusion within the membrane, ie Fick's law.

Region 3 (Above the Membrane)
Forced convection. Fick's law within boundary layer.

Join the regions using mass conservation.

Membrane TEWL Calibration Model

4. Fick meets Ohm - the Electrical Analogy

Fick's law can be re-cast as follows:-

$$I = J\,A = -A D_{VA}\frac{\partial r}{\partial z} \quad = \quad -A\,D_{VA}\frac{\Delta r}{\Delta z} \quad = \quad -\frac{\Delta r}{R}$$

where	$\boldsymbol{I} = \boldsymbol{JA}$	is the Flux
	$\boldsymbol{A}$	is the cross-sectional Area
	$\boldsymbol{D_{VA}}$	is the Mass Diffusion Coefficient
	$\boldsymbol{R} = D\boldsymbol{z}/\boldsymbol{AD_{VA}}$	is the Diffusion Resistance

Then, by analogy (see Wheldon & Monteith[1], for example):-

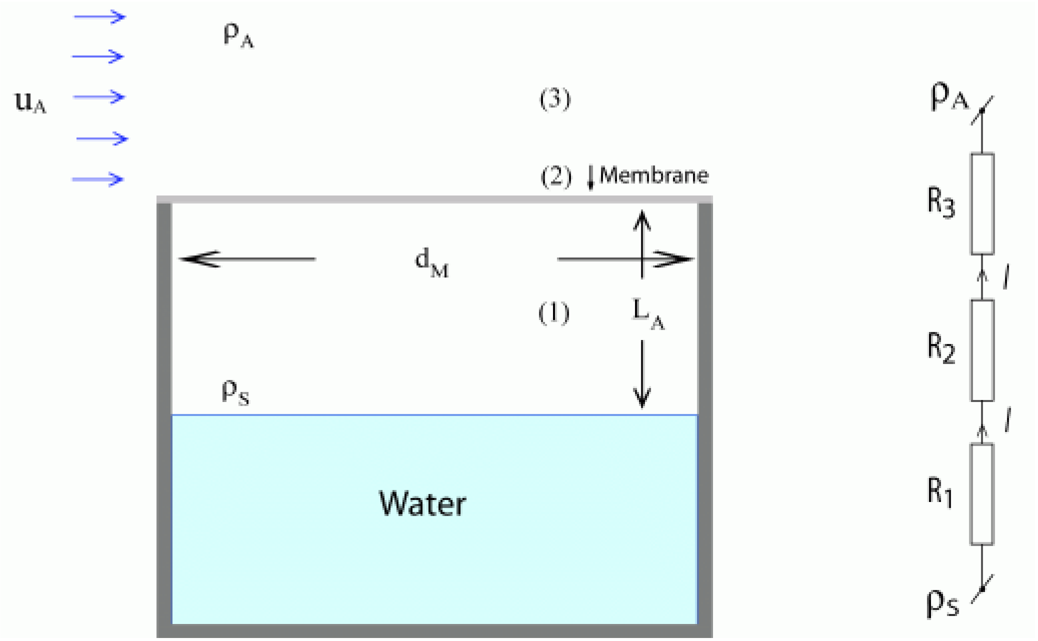
$\boldsymbol{I}$	is analogous to **electrical current**
Dr	is analogous to **potential difference**
$\boldsymbol{R}$	is analogous to **electrical resistance**

The analogy is useful, because you can use circuit theory to simplify the solution of complex problems.

[1] A E Wheldon & J L Monteith, *Performance of a Skin Evaporimeter*, Med Biol Comput, 18, 201-5, 1980.

Membrane TEWL Calibration Model

5. Electrical Equivalent of Leaky Cup



Membrane TEWL Calibration Model

6. Model Parameters

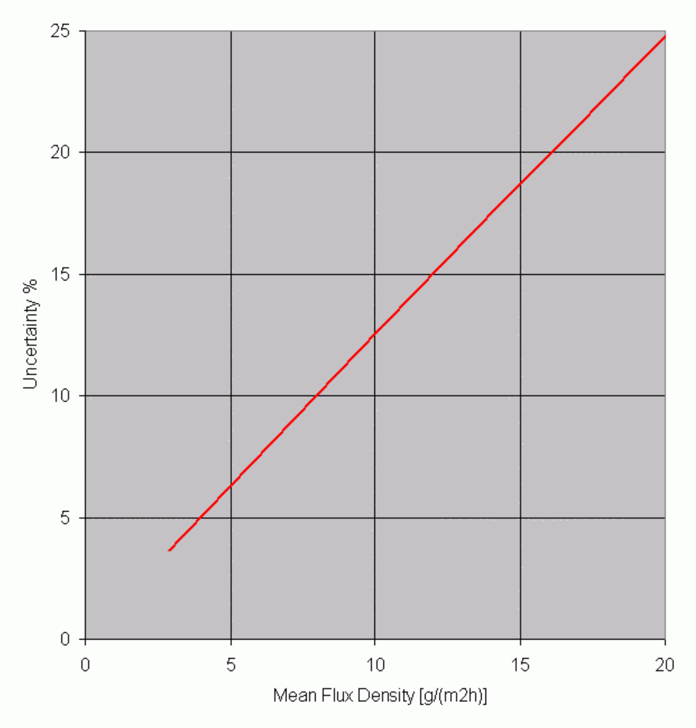
Ambient temperature:-	21 °C
Ambient RH	50 %
Membrane diameter	100 mm
Membrane-liquid separation	25 mm

Ambient air movement	0.02 - 0.3 ms^{-1}
∴ Ambient boundary layer	13.4 - 3.6 mm

NB:- These conditions are compatible with ASTM-96.

Membrane TEWL Calibration Model

Result 1:- Flux Uncertainty caused by Ambient Air Movement



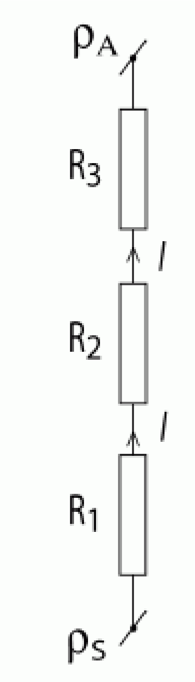
Note:-

1. The uncertainty is small for the low flux levels envisaged in ASTM-96.

2. The uncertainty is significant for the flux levels appropriate for TEWL calibration.

Membrane TEWL Calibration Model

Numerical Example:- Diffusion resistances at $J = 10\ gm^{-2}h^{-1}$



Open Air Boundary Resistance

R3 ~ 35 ± 20 (arb)

Membrane Resistance

R2 ~ 200 (arb)

Enclosed Air Resistance

R1 ~ 100 (arb)

The trouble is that all three resistances are significant.

For constant flux, you need

$$(R_1 + R_2) >> R_3$$

Constant Water Evaporation Device

Petri dish with Opsite membrane

Fig. 6. The constant water evaporation device. See the Section. "Intra- and inter-instumental variability" and Table 2.

This device cannot be relied upon to provide a constant flux for TEWL calibration.

Reproduced from:- *Guidelines for Transepidermal Water Loss (TEWL) Measurement*.
J Pinnagoda, R A Tupker, T Agner & J Serup, Contact Dermatitis, 22, 164-78, 1990.

Membrane TEWL Calibration Model

Open-chamber Modelling

Cylinder length	20 mm
Cylinder diameter	10 mm

Notes:-

1. Wheldon & Monteith's open-chamber model[1] was used.

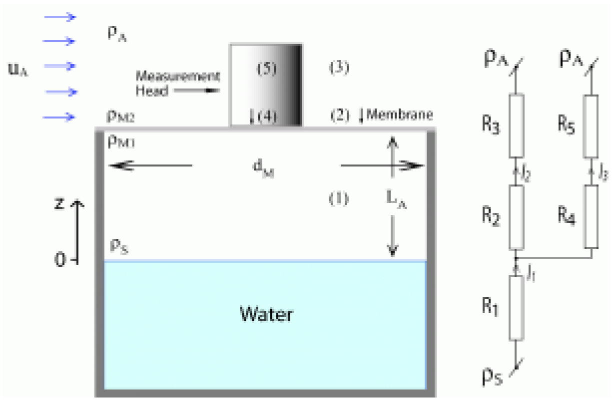
2. The effects from centrally placed sensors and foam pads have not been taken into account. These cause the diffusion resistance of the measurement head to increase.

3. The ambient and other conditions are as before.

[1] A E Wheldon & J L Monteith, *Performance of a Skin Evaporimeter*, Med Biol Comput, 18, 201-5, 1980.

Membrane TEWL Calibration Model

Result 2:- TEWL Calibration Method 1 (Exposed Membrane)



You now have two additional regions:-

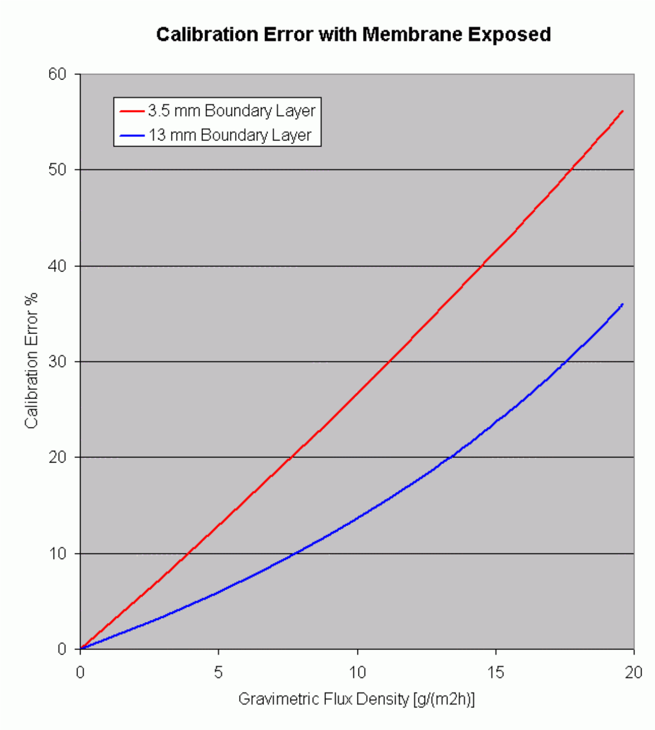
Region 4 (Membrane under Measurement Head)
Diffusion within the membrane, ie Fick's law.

Region 5 (Measurement Head)
Diffusion in air, ie Fick's law.

In general, the flux densities in the two branches will not be equal.

Membrane TEWL Calibration Model

Result 2:- Method 1 Calibration Error (Exposed Membrane)



Calibration Error calculated from:-

$$e = 100 \cdot \frac{J_G - J_H}{J_G}$$

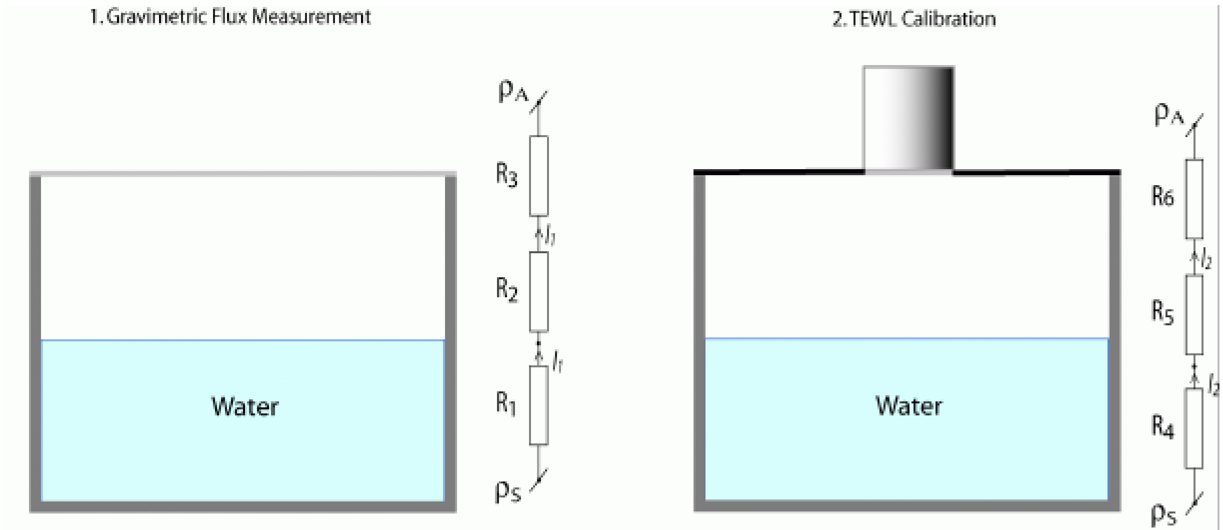
where

J_G = Gravimetric Flux Density

J_H = Measurement Head Flux Density

Membrane TEWL Calibration Model

Result 3:- TEWL Calibration Method 2 (Covered Membrane)

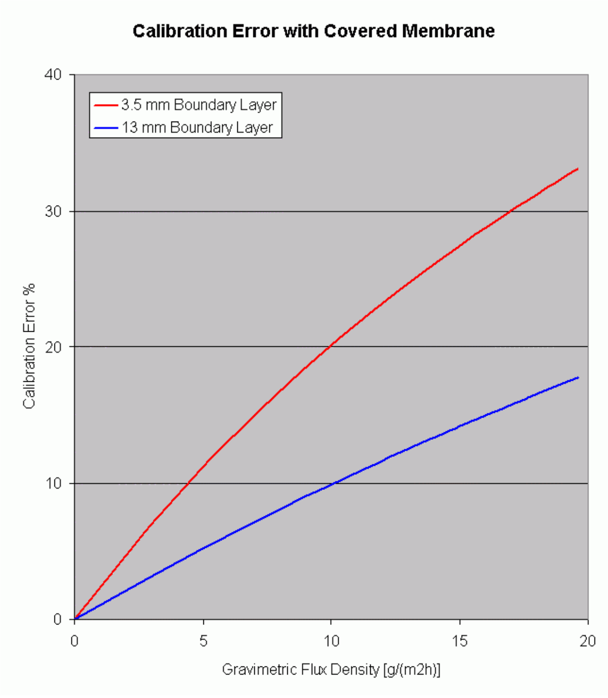


Gravimetric measurement of Flux Density from cup weight loss. You need a large membrane area for this.

Calibration of TEWL instrument with the membrane outwith the measurement head covered.

Membrane TEWL Calibration Model

Result 3:- Method 1 Calibration Error (Covered Membrane)



Calibration Error calculated from:-

$$e = 100 \cdot \frac{J_G - J_H}{J_G}$$

where

J_G = Gravimetric Flux Density

J_H = Measurement Head Flux Density

Conclusions

The Cup + Membrane system is NOT a constant flux device for TEWL Calibration.

Gravimetric flux density is NOT equal to Measurement Head flux density .

Therefore, ASTM-96 is NOT a good starting point for a reliable calibration.

Acknowledgements

Sponsors:-

UK Department of Trade and Industry

Fundacao para a Ciencia e Tecnologia, Portugal (Academic Exchange)