

Observation of Wicking Behavior of an ENDS Device Using Weight-Time Measurements

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Introduction & Objectives

- The rate of liquid uptake (wicking) of an e-vapor liquid is an important factor for the performance of an electronic nicotine delivery system (ENDS) device. A common method for quantifying the wicking rate uses Lucas-Washburn theory, where the time required for a liquid to travel a certain height in the material due to capillary action is determined
- Rapid e-liquid uptake and the size of wicks in ENDS devices limits the suitability of traditional methods
- Mass-time measurements offer an alternative to measuring penetration distance
- The weight uptake of liquid throughout the entire wick volume can be measured as opposed to only the visible outer surface in height-time measurements
- We sought a method that allows mass-time measurements for the MarkTen[®] wick to be determined in a reproducible manner
- Results of wicking rate measurements should correlate with liquid physical properties

Theory

Height-Time Lucas-Washburn Equation

$$h = \sqrt{\frac{r_{\text{eff}} \gamma_L \cos \theta_{\text{SL}}}{\eta_L}} \sqrt{t}$$
$$h \propto m$$

h = penetration distance
 t = time
 r_{eff} = effective pore radius
 γ_L = liquid surface tension
 θ_{SL} = solid liquid contact angle
 η_L = liquid viscosity

Weight-Time Lucas-Washburn Equation

$$m = \sqrt{\frac{(\varepsilon A_c \rho_L)^2 r_{\text{eff}} \gamma_L \cos \theta_{\text{SL}}}{2 \eta_L}} \sqrt{t}$$

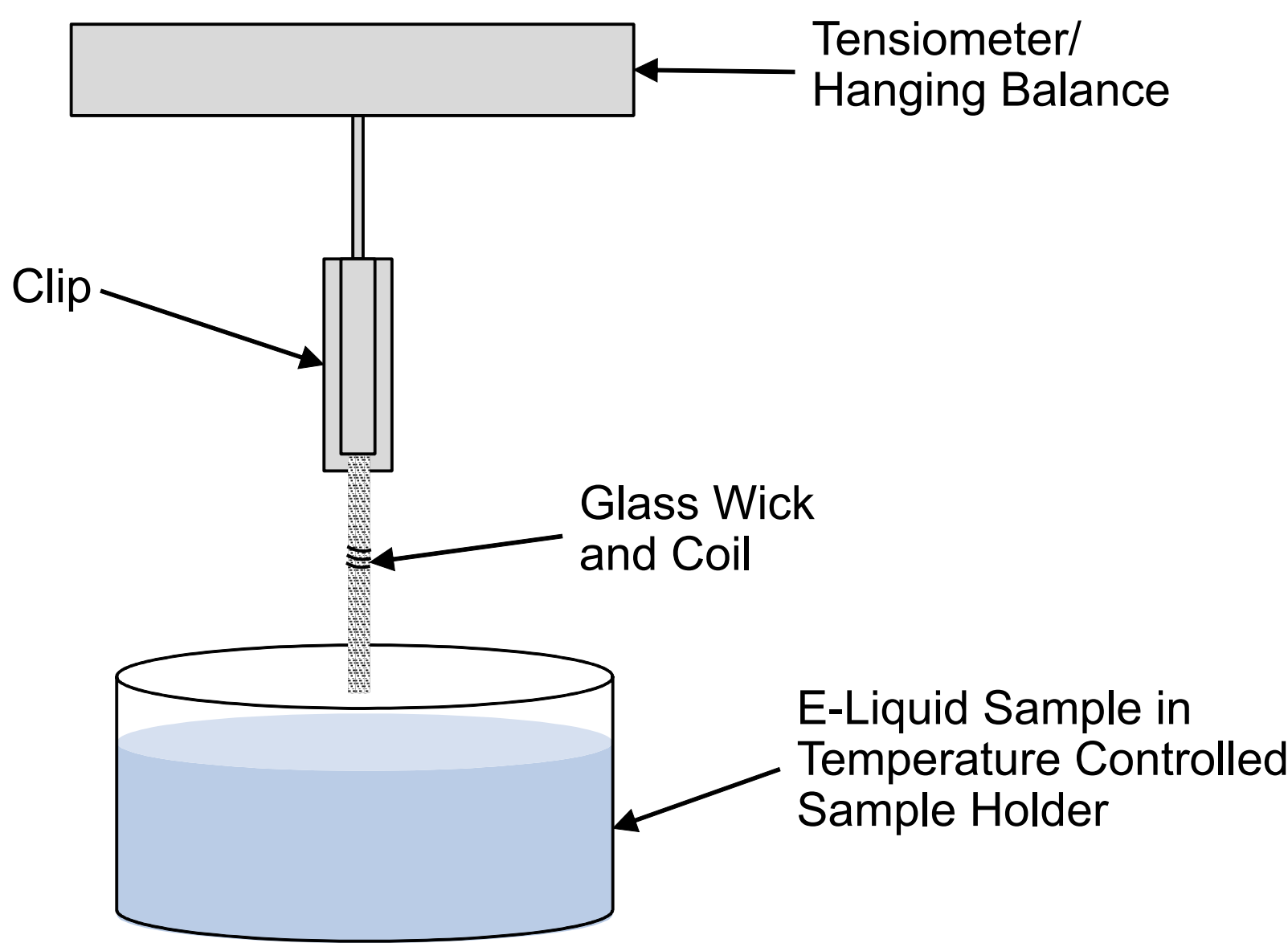
Wick and Liquid Parameters

$$m = k \sqrt{t} + b$$

Capillary Constant Mass-Correction Factor

m = mass uptake
 t = time
 ε = wick porosity
 A_c = cross-sectional area
 ρ_L = liquid density
 r_{eff} = effective pore radius
 γ_L = liquid surface tension
 θ_{SL} = solid liquid contact angle
 η_L = liquid viscosity

Experimental



- Tests were performed using five MarkTen[®] e-liquid formulations and six wicks from each of three lots (resulting in 18 trials)
- A Krüss K100 tensiometer was used for the wicking measurements performed at two temperatures, 25 and 50 °C
- Mass/time data was collected and the capillary constant and mass correcting factor determined by fitting data to the modified Lucas-Washburn equation
- Viscosity values were measured using a rheometer and surface tension was measured using by Wilhelmy Plate method on the tensiometer

Summary / Conclusions

- Wicking behavior of MarkTen[®] wick and coil assembly was measured at two temperatures (25 and 50 °C)
- Weight-time method developed using a tensiometer, and data was fit using modified Lucas-Washburn theory
- Rate law determined for wicking process up to 70% saturation
- Capillary constant results correlate linearly to e-liquid physical properties
- Further work required to extend method and theory to model wicks with >70% saturation

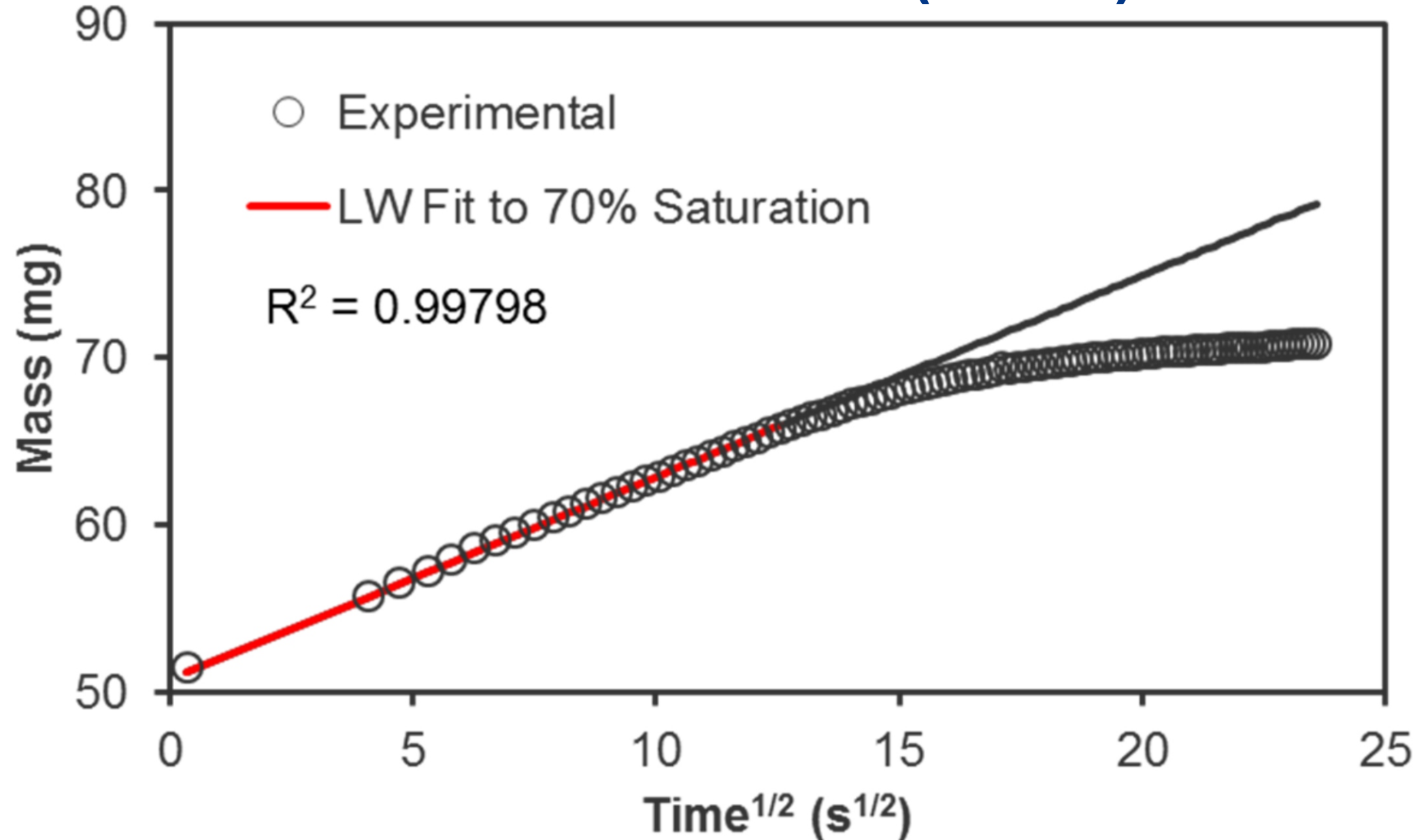
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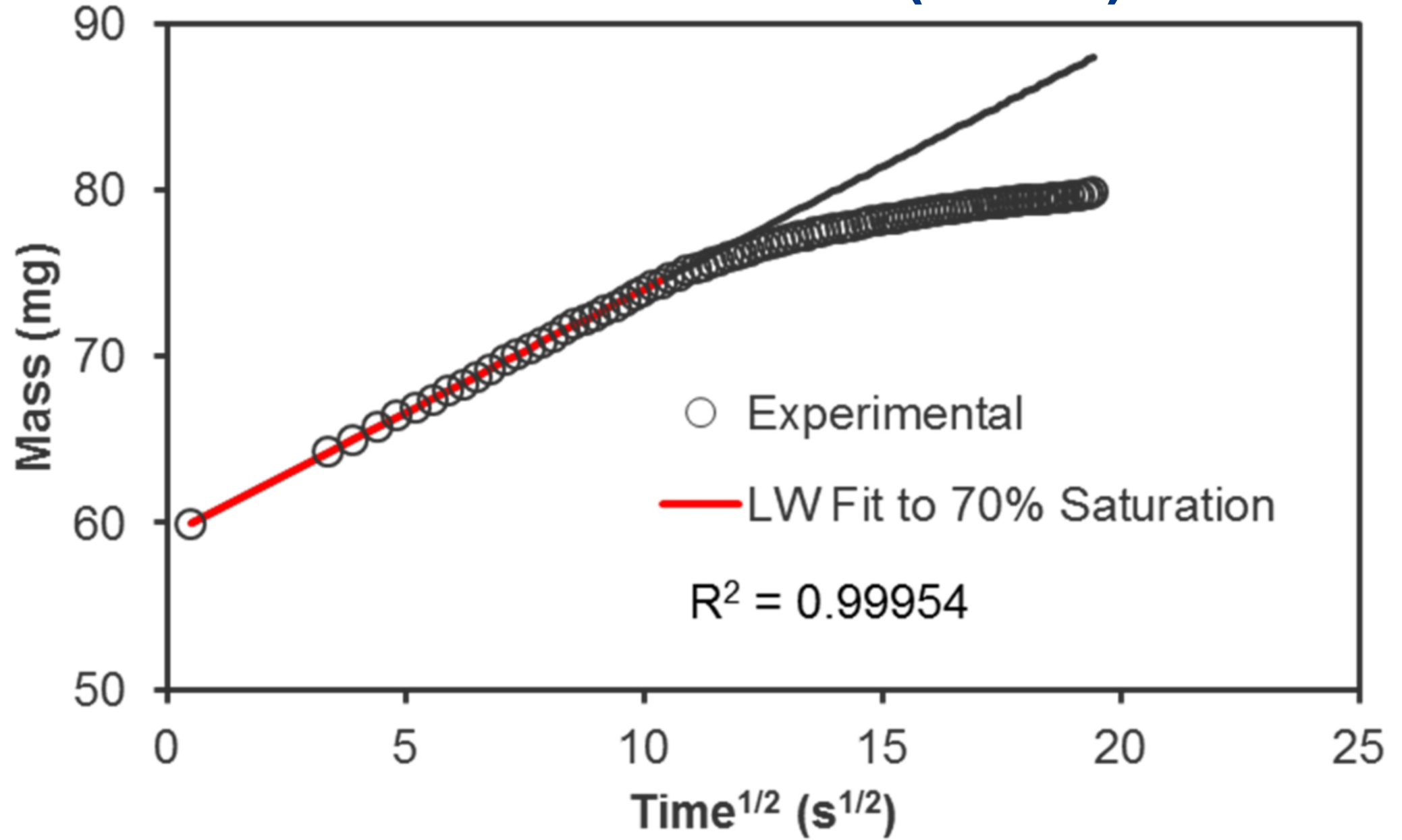
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Results

MarkTen[®] Classic (25 °C)



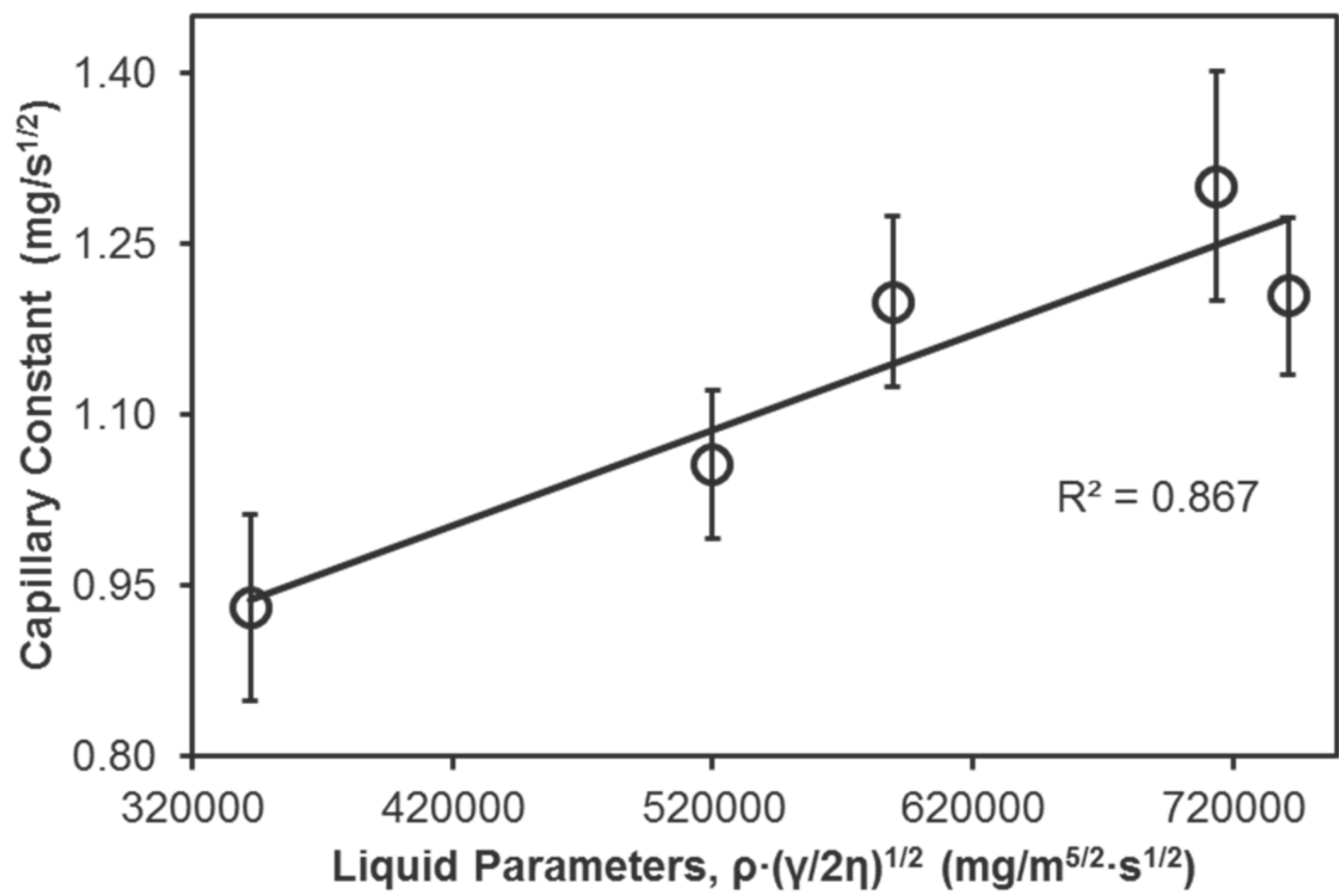
MarkTen[®] Classic (50 °C)



E-Liquid Formulation	Capillary Constant, k (mg/s ^{1/2})		Mass Correction Factor, b (mg)	
	25 °C	50 °C	25 °C	50 °C
MarkTen [®] Classic	1.20 ± 0.07	1.39 ± 0.08	54 ± 3	56 ± 3
MarkTen [®] Bold Classic	1.30 ± 0.10	1.35 ± 0.10	55 ± 4	56 ± 4
MarkTen [®] Menthol	1.20 ± 0.07	1.39 ± 0.13	43 ± 4	45 ± 4
MarkTen [®] Bold Menthol	1.06 ± 0.07	1.26 ± 0.05	44 ± 4	45 ± 3
MarkTen [®] Smooth Cream [®]	0.93 ± 0.08	1.21 ± 0.11	48 ± 3	50 ± 3

- Data shown are from a single repetition with MarkTen[®] Classic formulation at two temperatures, 25 and 50 °C
- Modified Lucas-Washburn equation is shown fit to the experimental data up to 70% saturation point
- Theory and experiment diverge as the wick saturation increases beyond 70%
- Results are very reproducible and repeatable, one standard deviation of the mean ($n = 18$) shown in the table, $\sigma < 10\%$
- Method is suitable for measuring wicking as a function of temperature with limits based on evaporation of e-liquid components

Correlation of Wicking Rate to Liquid Properties



- Results for wicking capillary constant are compared to liquid parameters showing linear correlation
- Viscosity measured using TAAR-G2 rheometer
- Surface Tension measured using platinum plate and surface tension method on Krüss K100 Tensiometer
- Density is estimated based on the Propylene Glycol/Glycerol/Water in each e-liquid formulation

E-Liquid Formulation	Viscosity, η (cP)	Surface Tension, γ (mN/m)	Estimated Density, ρ (g/cm ³)
MarkTen [®] Classic	57 ± 1	46.9 ± 0.2	1.16
MarkTen [®] Bold Classic	63 ± 3	47.8 ± 0.2	1.16
MarkTen [®] Menthol	57 ± 1	32.4 ± 0.1	1.11
MarkTen [®] Bold Menthol	71 ± 1	31.3 ± 0.3	1.11
MarkTen [®] Smooth Cream [®]	255 ± 10	43.5 ± 0.1	1.17