# 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

$$h = \sqrt{\frac{r_{\text{eff}}\gamma_L \cos\theta_{\text{SL}}}{\eta_{\text{L}}}}\sqrt{t}$$

$$h \propto m$$

$h$ = penetration distance
$t$ = time
$r_{\text{eff}}$ = effective pore radius
$\gamma_{\text{L}}$ = liquid surface tension
$\theta_{\text{SL}}$ = solid liquid contact angle
$\eta$ = liquid viscosity

### Weight-Time Lucas-Washburn Equation

$$m = \sqrt{\frac{(\varepsilon A_C \rho_{\text{L}})^2 r_{\text{eff}}\gamma_L \cos\theta_{\text{SL}}}{2\eta_{\text{L}}}}\sqrt{t}$$

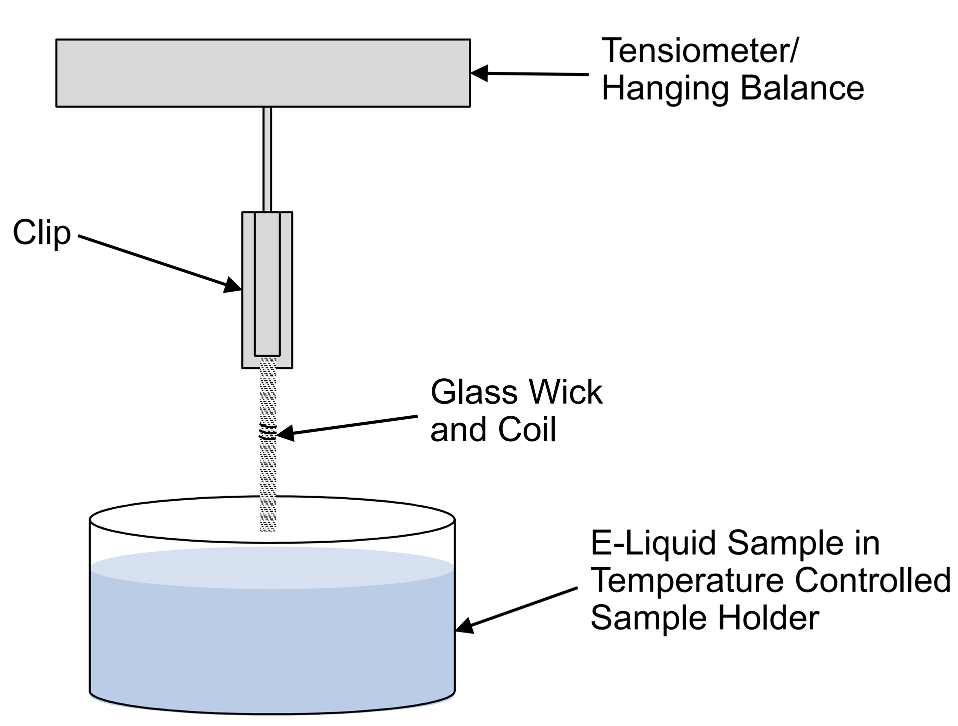
Wick and Liquid Parameters

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

Capillary Constant ($k$); Mass-Correction Factor ($b$)

$m$ = mass uptake
$t$ = time
$\varepsilon$ = wick porosity
$A_c$ = cross-sectional area
$\rho_{\text{L}}$ = liquid density
$r_{\text{eff}}$ = effective pore radius
$\gamma_{\text{L}}$ = liquid surface tension
$\theta_{\text{SL}}$ = solid liquid contact angle
$\eta$ = 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

## References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- Hamraoui, A.; Nylander, T. Analytical Approach for the Lucas-Washburn Equation. J. Colloid and Interface Sci. 2002, 250, 415-421. DOI: 10.1006/jcis.3003.8228.
- ASTM C1559-15. Standard Test Method for Determining Wicking of Fibrous Glass Blanket Insulation (Aircraft Type). ASTM International: West Conshohocken, March 2015.


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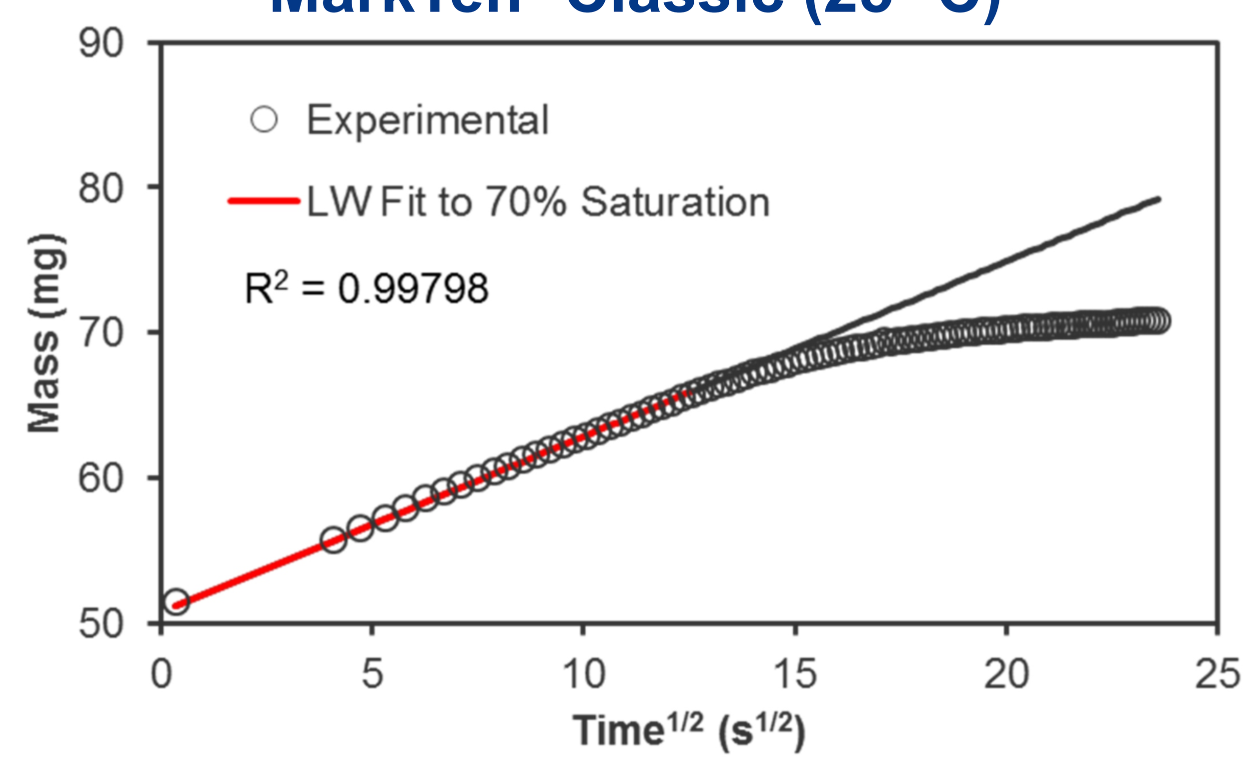
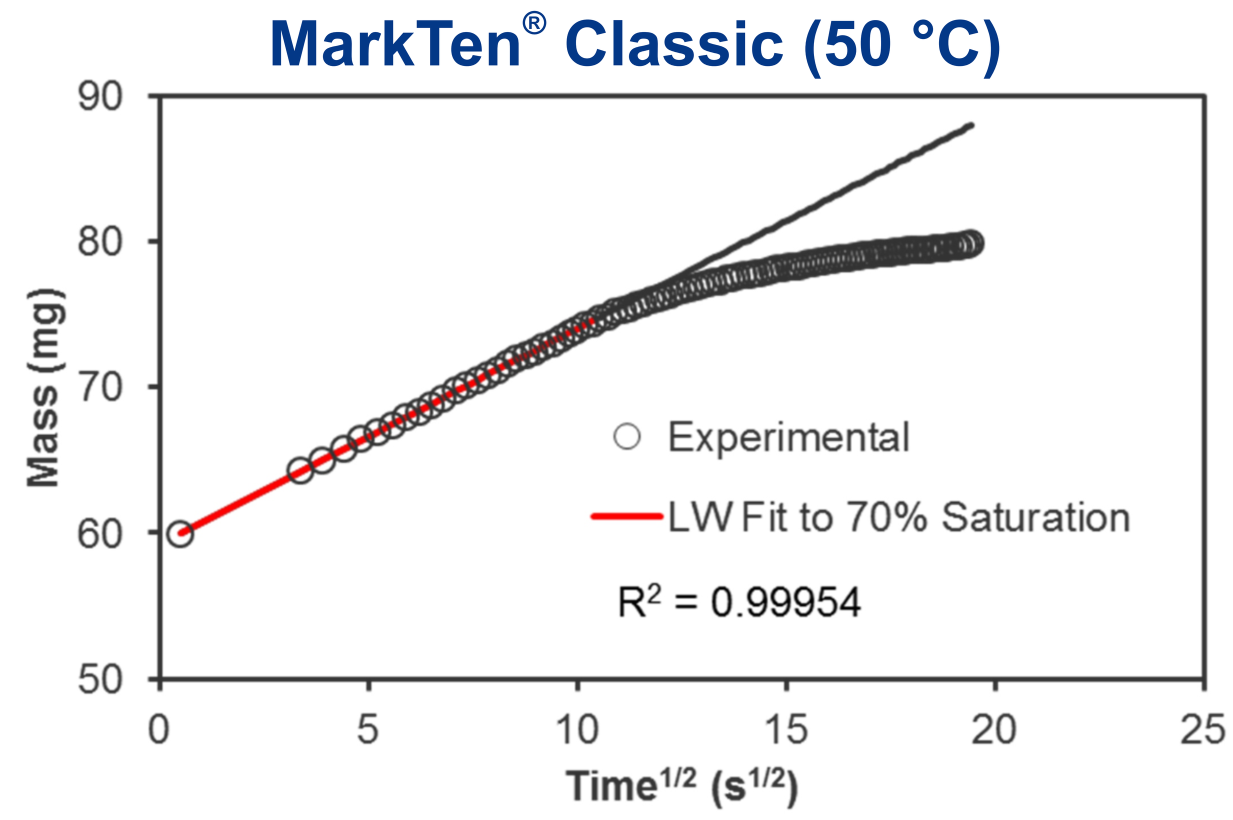
## Results

### MarkTen® Classic (25 °C)



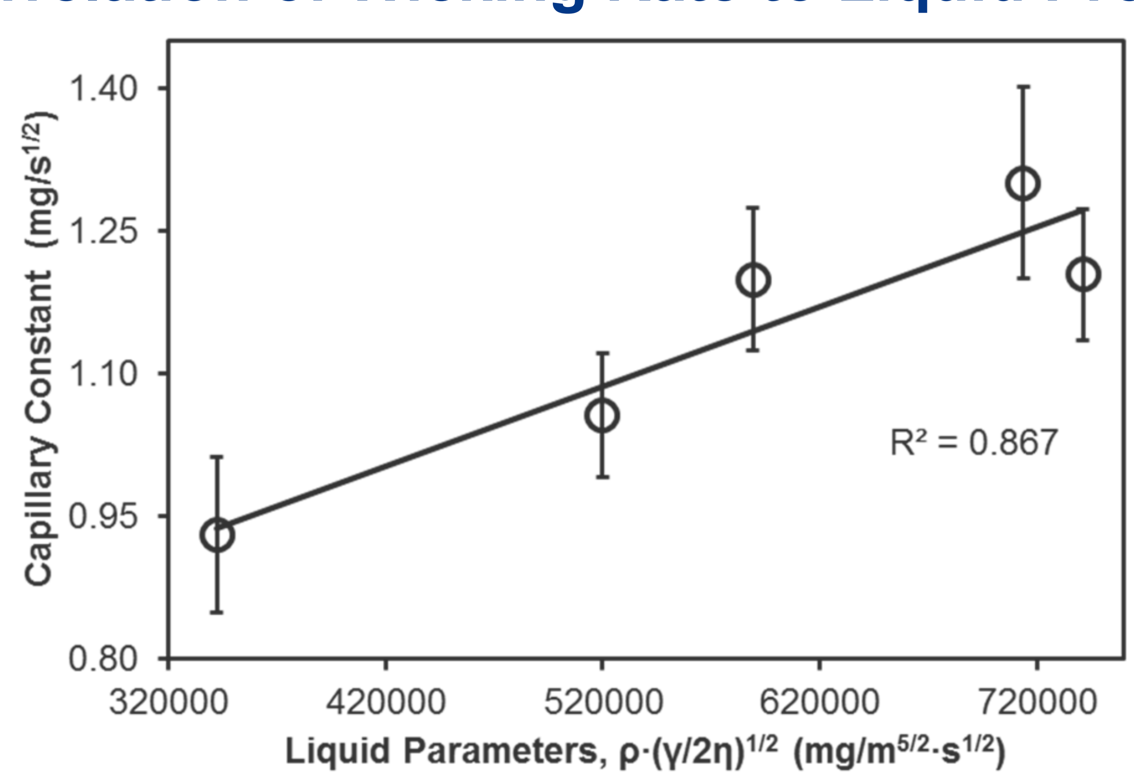

### MarkTen® Classic (50 °C)




| 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, $\eta$ (cP) | Surface Tension, $\gamma$ (mN/m) | Estimated Density, $\rho$ (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 |