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# Calibration of In-line Acoustic Wave Viscosity Sensors for Measurement of Printing Inks

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**Abstract**

A thickness shear mode acoustic wave viscosity sensor has been developed for wide scale use in the flexographic printing industry. The sensor is based on the use of a two-port monolithic crystal filter bulk wave device and the correlation of loss to acoustic viscosity has been successfully used to control the viscosity of printing inks in high volume printing. The operation of the sensor is reviewed and the development of a calibration method to translate the acoustic viscosity into units of cup-seconds is presented. Use of the calibration methods has been shown to enable the end user printer to report viscosity measurements in any units of viscosity measurement desired with excellent accuracy.

**Key words:** viscosity, sensor, printing, calibration and ink

## Introduction

Within the flexographic printing industry, the demand for faster printing speeds, improved print quality and quick set up time continues to grow. Increasingly, the ink viscosity control system in flexographic printing presses is critical to achieving these goals. Within this industry, ink viscosity measurements using a viscosity cup and a stopwatch is still considered to be the historical standard that all other viscosity measurement techniques are referenced against. Even with the latest advancements in viscosity measurement technology, the units of viscosity measurement that printers most often use when setting up the viscosity of the printing ink are still based on the units of cup-seconds. That is partly because printers have decades of printing knowledge based on the use of viscosity cups and often the optimal ink viscosities are known in units of cup-seconds for a particular type of viscosity cup. To simplify viscosity correlation procedures, a viscosity sensor solution provider needs to make it easy to translate from one set of sensor viscosity measurement units into any type of viscosity cup in units of cup-seconds. While there are numerous viscosity cups available, two viscosity cups, EZ Zahn#2 and Din 4, are the most commonly used.

## Operation of the Acoustic Wave Sensor

The viscosity sensor is built around a 5.25MHz, 2-port monolithic crystal filter sensing element [1-2]. The excitation of the sensing element is implemented using a common emitter amplifier oscillator circuit, while RF detectors are used to quantify the signal levels measured at the input and output of the MCF. Factory calibration of the sensor is accomplished by correlating the loss of the sensing element to the product of density times absolute viscosity, which is also known as acoustic viscosity (AV). The sensing element and electronics are all packaged in a bolt style housing shown in Fig. 1.


*Fig. 1. Packaged bulk wave viscosity sensor.*

## A Simple, Reference Temperature Calibration Model for Printing Inks

To develop a simple equation that will allow us to directly translate sensor AV into a viscosity cup-seconds measurement, we will momentarily ignore the effects of temperature on the cup viscosity and sensor measurements. To legitimately do this, we will ensure that that all sensor and viscosity cup measurements are taken at a single reference temperature or calibration temperature called $T_{ref}$. This then allows us to define the simple relationship for cup-seconds, eq. (1).

$$cup_{calc} = M_{ref} \cdot AV_{ref} + B_{ref} \text{ ,} \tag{1}$$

where $M_{ref}$ and $B_{ref}$ are calibration constants that relate the sensor viscosity ($AV_{ref}$) to the viscosity cup value ($cup_{calc}$) in units of cup-seconds at a single reference temperature ($T_{ref}$). Fig. 2 shows the EZ Zahn#2 cup viscosity versus sensor AV for various concentrations of solvent and water based Flint inks at 20°C. As shown, the relationships are linear and the calibration coefficients, $M_{ref}$ and $B_{ref}$, are easily seen to be the slopes and intercepts of the linear curves for the various inks.

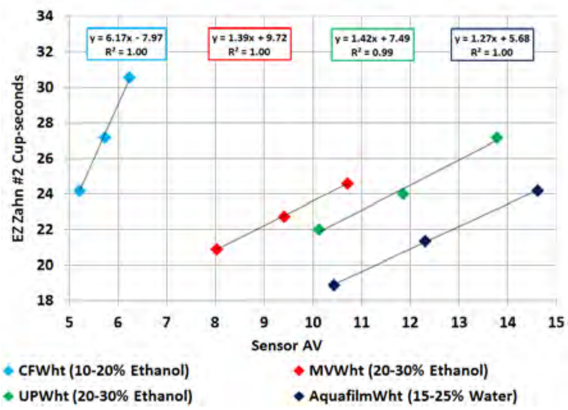


*Fig. 2. Linear EZ Zahn#2 cup-seconds viscosity vs. sensor AV for various concentrations of Flint solvent and water based printing inks at $T_{ref}$ = 20°C.*

In reality, only two sets of sensor and cup viscosity measurements are required to calculate the slope and intercept calibration coefficients using two concentrations of a particular ink. One approach would be to take one set of sensor and cup measurements with an ink solution slightly thicker than the optimal concentration and one set of sensor and cup measurements with an ink that is slightly thinner than the ideal viscosity solution used for printing. Using these two sets of measurements at the reference temperature then allows one to calculate the calibration coefficients using the following equations:

$$M_{ref} = \frac{cup_{ref2} - cup_{ref1}}{AV_{ref2} - AV_{ref1}} \tag{2}$$

$$B_{ref} = cup_{ref1} - M_{ref} \cdot AV_{ref1} \tag{3a}$$

$$B_{ref} = cup_{ref2} - M_{ref} \cdot AV_{ref2} \text{ ,} \tag{3b}$$

where the two sets of sensor AV and viscosity cup measurements taken at a constant reference temperature ($T_{ref}$) have the following form:

<u>Ink Solution 1: Higher Viscosity Solution</u>

($T_{ref}$ , $AV_{ref1}$, $cup_{ref1}$)

<u>Ink Solution 2: Lower Viscosity Solution</u>

($T_{ref}$ , $AV_{ref2}$, $cup_{ref2}$)

Using eq. (2-3) and the data from Tab. 1 for a viscosity sensor and an EZ Zahn#2 viscosity cup, calibration coefficients are calculated for the various white Flint inks at a reference temperature of $T_{ref}$ = 20°C (Tab. 2).

*Tab. 1: Viscosity Sensor and EZ Zahn#2 Viscosity Cup Measurements at 20°C.*

| Ink Type | % Ethanol or Water | Sensor (AV) | Cup (cup-sec) |
|---|---|---|---|
| MV | 20 | 10.71 | 24.59 |
| MV | 30 | 8.03 | 20.87 |
| UP | 20 | 13.78 | 27.17 |
| UP | 30 | 10.13 | 22.01 |
| CF | 10 | 6.23 | 30.57 |
| CF | 20 | 5.20 | 24.21 |
| Aquafilm | 15 | 14.62 | 24.18 |
| Aquafilm | 25 | 10.43 | 18.86 |

*Tab. 2: Viscosity Sensor Calibration Coefficients for Various Inks at $T_{ref}$ = 20°C.*

| Ink Type | Solution Measurement Range | $M_{ref}$ | $B_{ref}$ |
|---|---|---|---|
| MV | 20-30% Ethan. | 1.39 | 9.70 |
| UP | 20-30% Ethan. | 1.41 | 7.74 |
| CF | 10-20% Ethan. | 6.17 | -7.87 |
| Aquafilm | 15-25% Water | 1.27 | 5.61 |

Therefore, if one could precisely control the reference temperature to 20°C, then the equation one would use to translate sensor AV into EZ Zahn#2 cup-seconds for MV White ink with ethanol concentrations range 20 to 30% would be the following:

**cup = 1.39 * AV + 9.70**

Unfortunately, precise temperature control of printing inks in a flexographic press is not always a feature that exists and one needs to understand the impact temperature will have on the viscosity of the printing ink.

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### Ink Viscosity Dependencies on Temperature

While all fluids have a strong, non-linear viscosity versus temperature dependence over a wide range of operating temperature, printing inks tend to stay close to the ambient room conditions where the printing press is installed with only small variation in the temperature of the printing ink. Fortunately, over this narrow range of operating temperature, the ink viscosity can be assumed to be a linear function of temperature. Fig. 3 shows the EZ Zahn#2 viscosity cup-seconds versus temperature behavior, while Fig. 4 shows the sensor AV versus temperature relationship. There are two observations to note when reviewing Fig. 3 and Fig. 4. First, as expected over a narrow temperature range, the viscosity versus temperature behavior is very linear. If we already know the viscosity cup-seconds or sensor AV slope for a given solution of ink by prior characterization, then we can use the known viscosity cup-seconds or sensor AV slopes to translate a cup or sensor measurement from the measurement temperature to a reference temperature with minimal error. Second, over a small concentration range of the ink solution (eg. near the optimal ink concentration), the viscosity slope changes very little and the slope can be assumed to be a constant value over a small range of %ethanol or %water. As will be shown below, we will assume the viscosity cup-seconds or AV slopes are equal to the slopes at the optimal ink concentration that results in the best print quality.

### Translating Viscosity Measurements from One Temperature to Another

Now that we understand how viscosity changes relative to temperature, we can use the known cup or AV viscosity slopes to translate the viscosity from the measurement temperature to any reference temperature we choose. Obtaining the cup viscosity slope ($m_{cup}$) from Fig. 3 for a given ink solution, the cup viscosity ($cup_{ref}$) at the reference temperature ($T_{ref}$) can be calculated using eq. (4).

$$\mathrm{cup}_{ref} = \mathrm{cup}_m + m_{cup} \cdot (T_{ref} - T_m)\,, \qquad (4)$$

where $cup_m$ is the cup viscosity measurement at the measurement temperature ($T_m$), $m_{cup}$ is the known cup viscosity versus temperature slope and $T_{ref}$ is the reference temperature.

Similarly, for sensor AV, acquiring the AV viscosity slope ($m_{av}$) from Fig. 4 for a given ink solution, the AV viscosity ($AV_{ref}$) at the reference temperature ($T_{ref}$) can be calculated

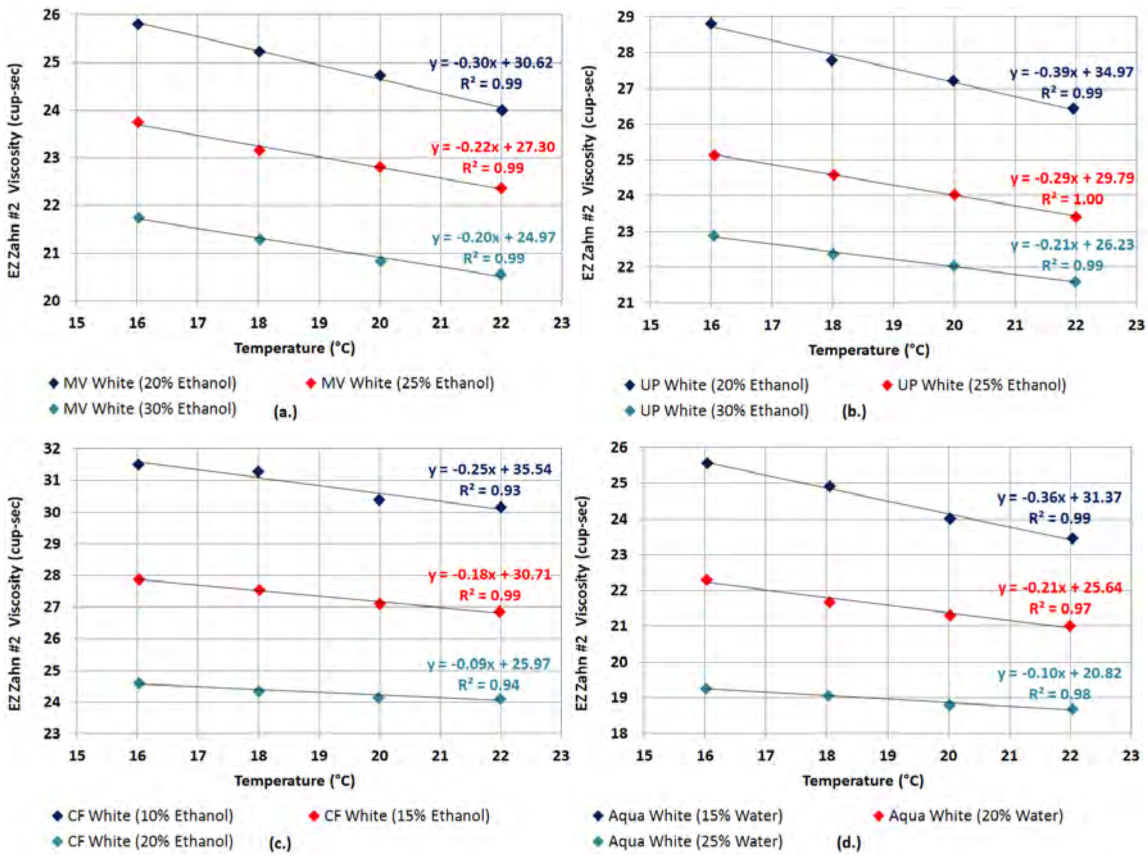


*Fig. 3. Linear EZ Zahn#2 cup viscosity versus temperature behavior for various concentrations of Flint solvent and water based printing inks over the narrow temperature range of 16 to 22°C.*

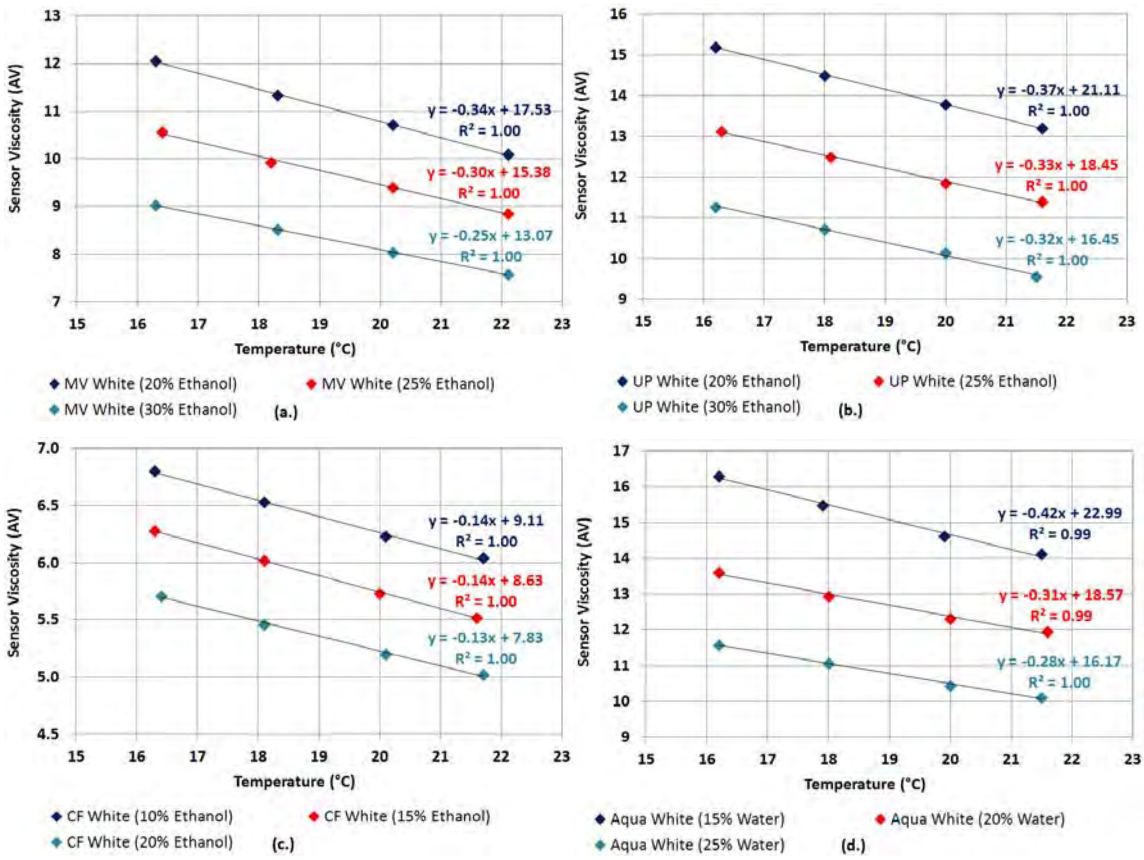


*Fig. 4. Linear sensor AV viscosity versus temperature behavior for various concentrations of Flint solvent and water based printing inks over the narrow temperature range of 16 to 22°C.*

using eq. (5) below.

$$AV_{ref} = AV_m + m_{av} \cdot (T_{ref} - T_m)\,, \qquad (5)$$

where $AV_m$ is the sensor viscosity at the measurement temperature ($T_m$), $m_{av}$ is the known AV viscosity versus temperature slope and $T_{ref}$ is the reference temperature.

An example reference cup calculation is shown in Fig. 5, where $m_{cup}$ is assumed to be -0.22 for concentrations MV white ink ranging from 20 to 30% ethanol (Fig. 3). An example reference sensor AV calculation is also shown in Fig. 6,

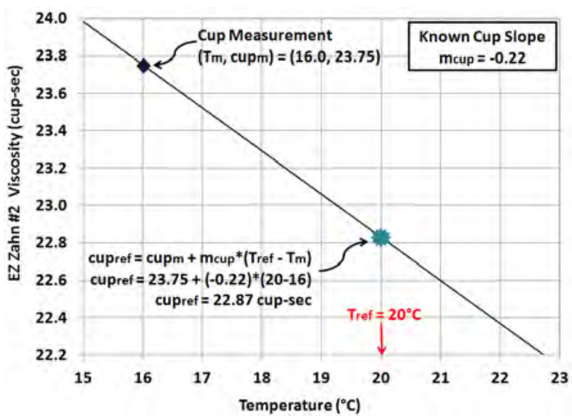


*Fig. 5. Translating a cup measurement from the measurement temperature to a reference temperature for MV white ink (20 to 30% ethanol).*

where $m_{av}$ is assumed to be -0.30 (Fig. 4) for the same ink and ethanol concentrations. As shown in the figures, the calculation translates the cup and sensor AV measurements from the measured temperature to the reference temperature using the known cup and sensor AV viscosity slopes and the difference between the reference and measurement temperatures.

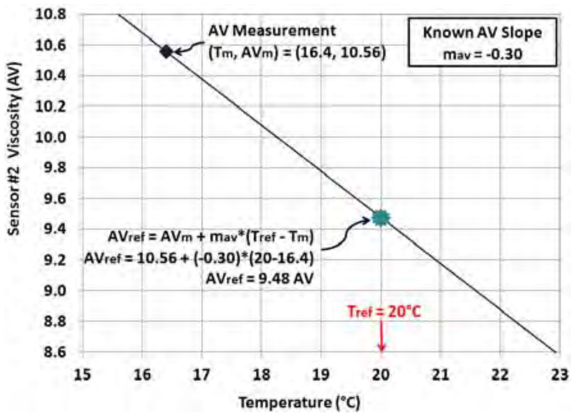


*Fig. 6. Translating a sensor measurement from the measurement temperature to a reference temperature for MV white ink (20 to 30% ethanol).*

It will be seen shortly that it may be necessary to translate a cup viscosity value from the reference temperature back to the original measurement temperature. The process is exactly the same as translating a viscosity measurement from the measurement temperature to the reference temperature. To prevent confusion, we will designate the reference cup value as $cup_{calc}$ and the translated cup value as $cup_{final}$. Assuming we already know the cup viscosity slope ($m_{cup}$) for a given ink solution, the cup viscosity ($cup_{final}$) at the original measurement temperature ($T_m$) can be calculated using eq. (6).

$$cup_{final} = cup_{calc} + m_{cup} \cdot (T_m - T_{ref}), \qquad (6)$$

where $cup_{calc}$ is the cup viscosity at the reference temperature ($T_{ref}$), $m_{cup}$ is the known cup viscosity versus temperature slope (Fig. 3) and $T_m$ is the original measurement temperature.

**Calibrating a Viscosity Sensor to Report in Units of Cup-Seconds**

The sensor calibration process is illustrated in Fig. 7. If the calibration is done at a reference temperature ($T_{ref}$), the correlation from AV to cup-seconds follows the simple (cup=M*AV+B) relationship defined by eq. (1). The user can take a first set of measurements ($T_{m1}$, $AV_{m1}$, $cup_{m1}$) at any temperature with the first ink solution higher in viscosity than required by the optimal print quality. Next, the user can take a second set of measurements ($T_{m2}$, $AV_{m2}$, $cup_{m2}$) at any temperature and at a viscosity slightly lower than required by the optimal print quality. Assuming that the AV and cup viscosity temperature slopes do not change significantly across the two solutions of ink, the two sets of measurements can be transformed to the same reference temperature using eqs. 4-5 resulting

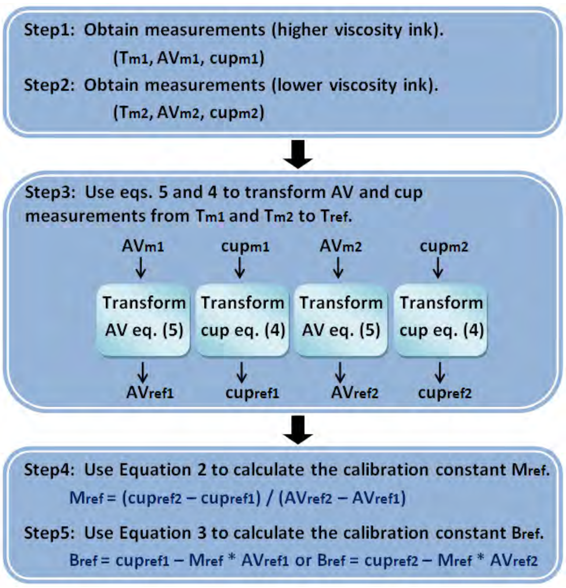


*Fig. 7. Flow chart illustrating the sensor calibration procedure.*

in two sets of transformed measurements ($T_{ref}$, $AV_{ref1}$, $cup_{ref1}$) and ($T_{ref}$, $AV_{ref2}$, $cup_{ref2}$). The calibration coefficients, $M_{ref}$ and $B_{ref}$, can then be calculated at the reference temperature using eqs. (2-3).

Using the sensor and cup measurements and known viscosity slopes listed in Tab. 3, the calibration procedure illustrated in Fig. 7 will result in the following calibration coefficients at a reference temperature of 20°C for MV ink.

**$T_{ref}$ = 20.0 $M_{ref}$ = 1.29 $B_{ref}$ = 9.93**

**cup = 1.29 * AV + 9.93**

*Tab. 3: MV White Calibration Data and Known Viscosity Slopes for the EZ Zahn#2 cup and Sensor*

| % Eth | T (°C) | Sen (AV) | EZ#2 (sec) | $m_{av}$ | $m_{cup}$ |
|---|---|---|---|---|---|
| 20 | 16.3 | 12.75 | 25.75 | -0.30 | -0.22 |
| 30 | 18.3 | 9.01 | 21.26 | | |

**Calculating Cup-Seconds Using Sensor Temperature and Viscosity**

Now that we understand how to calibrate a sensor, we can review the whole process of actually taking a sensor temperature and AV measurement and translating the sensor AV measurement into units of cup seconds (Fig. 8). The first step in the procedure is to obtain a temperature ($T_m$) and sensor viscosity ($AV_m$) measurement. Next, using the prior knowledge of the AV viscosity versus temperature slope ($m_{av}$), you transform the measurement ($AV_m$) to the reference sensor viscosity ($AV_{ref}$) at the reference temperature ($T_{ref}$) using eq. (5). Now that the sensor viscosity is at the reference temperature, you can use the correlation eq. (1) to calculate the cup viscosity value at the reference temperature. Finally, using the prior knowledge of the cup viscosity versus temperature slope ($m_{cup}$), transform the reference cup viscosity ($cup_{calc}$) to the actual cup value ($cup_{final}$) at the actual measurement temperature ($T_m$) using eq. (6).

Referring to Tab. 4, measurements of sensor temperature and AV viscosity in various MV white ink solutions were transformed into cup-seconds for an EZ Zahn#2 viscosity cup. The second and third columns of Tab. 4 are the sensor temperature and sensor AV measurements, respectively. The fourth column contains calculated values of AV translated to the reference temperature, while the fifth column contains the calculated cup value at the reference temperature using the calibration coefficients $M_{ref}$ and $B_{ref}$. Column six contains the final cup value translated back to the actual

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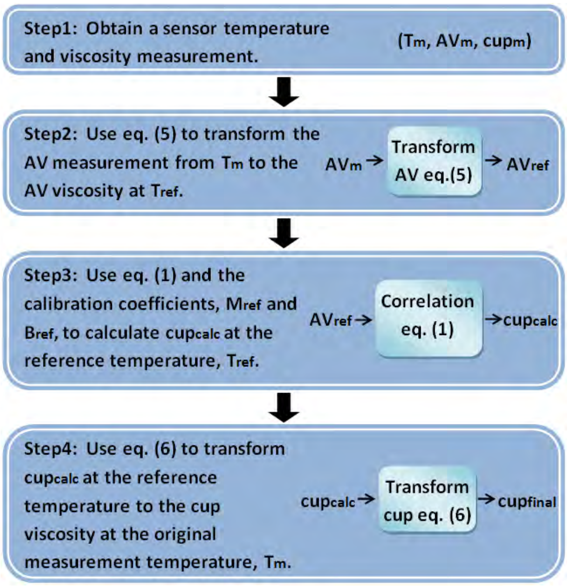


*Fig. 8. Flow chart illustrating the procedure to calculate cup-seconds from a sensor measurement using the calibration coefficients.*

measurement temperature and column seven has some actual cup measurements for comparison. The calculated cup viscosity is plotted along with the actual cup measurements and the resulting percent cup-seconds error in Fig. 9 with excellent results.

## Summary and Conclusions

This paper reviewed the general operation of an acoustic wave viscosity sensor and then presented a simple calibration model for translating sensor AV directly into cup-seconds at a constant reference temperature. The temperature dependencies of the sensor AV and cup viscosity were reviewed in detail and the process of translating a viscosity measurement from the measurement temperature to a reference temperature was shown allowing the simple calibration model to be implemented. Then it was shown how to calibrate a viscosity sensor at the reference temperature and an example calibration coefficient calculation was reviewed for MV white ink. Finally, subsequent measurements of sensor viscosity were then transformed into cup-seconds and compared to actual EZ Zahn#2 viscosity cup measurements with very good agreement.

## Acknowledgements

Special thanks goes out to Fisher & Krecke for supplying ink samples to carry out the ink calibration study. Gratitude also goes out to Gordon Whitelaw and Wolfgang Brusdeilins for providing much guidance on the requirements of in-situ ink calibration of viscosity sensors. We greatly appreciate the support and much needed feedback that helped to guide us in the development of this calibration method.

*Tab. 4: Sensor Measurements, Cup Calculations and Actual Cup Measurements ($T_{ref}$ = 20°C).*
*$M_{ref}$ = 1.29, $B_{ref}$ = 9.93, $m_{av}$ = -0.30 and $m_{cup}$ = -0.22*

| % Eth | $T_m$ | $AV_m$ | $AV_{ref}$ | cup calc | cup final | cup act. |
|---|---|---|---|---|---|---|
| 20 | 16.3 | 12.8 | 11.6 | 25.0 | 25.8 | 25.8 |
| 20 | 18.2 | 12.1 | 11.5 | 24.8 | 25.2 | 25.2 |
| 20 | 20.1 | 11.4 | 11.4 | 24.7 | 24.7 | 24.6 |
| 20 | 22.1 | 10.8 | 11.4 | 24.7 | 24.2 | 24.0 |
| 25 | 16.4 | 10.9 | 9.8 | 22.6 | 23.4 | 23.6 |
| 25 | 18.2 | 10.3 | 9.8 | 22.5 | 22.9 | 23.2 |
| 25 | 20.2 | 9.7 | 9.8 | 22.6 | 22.5 | 22.8 |
| 25 | 22.1 | 9.2 | 9.8 | 22.6 | 22.2 | 22.3 |
| 30 | 16.4 | 9.6 | 8.5 | 20.9 | 21.7 | 21.6 |
| 30 | 18.3 | 9.0 | 8.5 | 20.9 | 21.3 | 21.3 |
| 30 | 20.2 | 8.5 | 8.6 | 21.0 | 21.0 | 20.9 |
| 30 | 22.1 | 8.0 | 8.6 | 21.1 | 20.6 | 20.5 |

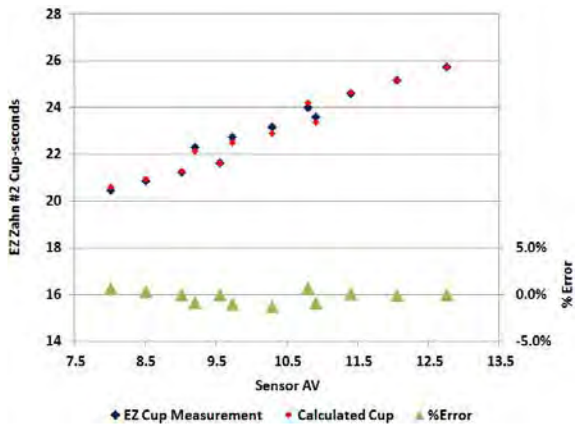


*Fig. 9. Cup calculations calculated from sensor temperature and viscosity measurements are compared to actual EZ Zahn#2 cup measurements.*

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