A Comprehensive Analysis of Viscosity Measurements

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Abstract

Viscosity, the measure of a fluid's resistance to flow, is one of the most evaluated and controlled parameters in the shell room. Viscosity is a universally accepted industry test that offers a quick and easy go/no go check to determine if a slurry is fit for use. Using a flow cup, the viscosity measurement is determined by the time it takes for the cup to completely empty after being submerged then extracted from a slurry. Too high of a slurry viscosity could result in insufficient shell coverage in difficult geometries, extended dry times or an increase in shell material usage. If viscosity is too low, the shell may not be strong enough to handle the stresses associated with dewax, burnout and casting.

Viscosity measurement is subject to a great deal of variation based upon equipment and methods used, as well as inconsistencies between operators. This paper will present a comprehensive analysis on the impact these variations have to the accuracy and precision of the viscosity measurement; specifically exploring results from various flow cups, end points, operators and slurry types. From these results, we will conclude best practice methods and equipment for repeatability of viscosity measurements. A correlation of the methods and equipment will also be determined for cross referencing the measurements.

Background

Viscosity is a physical property of fluids; it is a measurement of a material’s resistance to flow (The Editors of Encyclopedia Britannica, 2018). Materials that are thick or do not flow easily have a higher viscosity, whereas materials that are thin and do flow easily have a lower viscosity. Understanding the viscosity of a material, or how it will flow, is important when determining how to best handle the material. If the viscosity is controlled within a predetermined range, the flow properties can be controlled as well.

The viscosity of a material can be quantified as dynamic or kinematic viscosity. Dynamic viscosity measures the fluid's resistance to flow when an external force is applied to it. Kinematic viscosity represents the ability of a fluid to flow under the weight of gravity (Robert G. McGregor, 2009). The unit of measure for kinematic viscosity is the Stoke (St) or centi-Stoke (cSt). To better comprehend kinematic viscosity, a list of typical liquids and their viscosities is shown in Table 1.

Centistokes (cSt)	**Typical Liquid**
1	Water
4	Milk
15.7	No. 4 fuel oil
20.6	Cream
43.2	Vegetable oil
110	SAE 10 oil
220	Tomato juice
440	SAE 30 oil

Centistokes (cSt)	**Typical Liquid**
1100	Glycerin
1735	SAE 50 oil
2200	Honey
4500	Glue
6250	Mayonnaise
10800	Molasses B
19000	Sour cream
19600	SAE 70 oil

Table 1

A common tool used to measure kinematic viscosity (referred to as just viscosity for the remainder of this paper) is a flow cup. A flow cup is a precision instrument that is used to measure the efflux time of a fluid from the cup. Typical flow cups are shown in Figure 1. The distinguishing characteristics of the flow cup are the cup itself and the hole at the bottom of the cup.

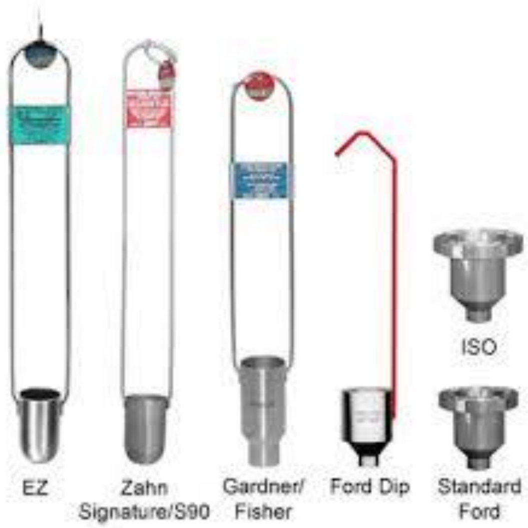


Figure 1 – Flow Cup Examples (Gardco, n.d.)

A typical procedure for determining viscosity with a flow cup is as follows:

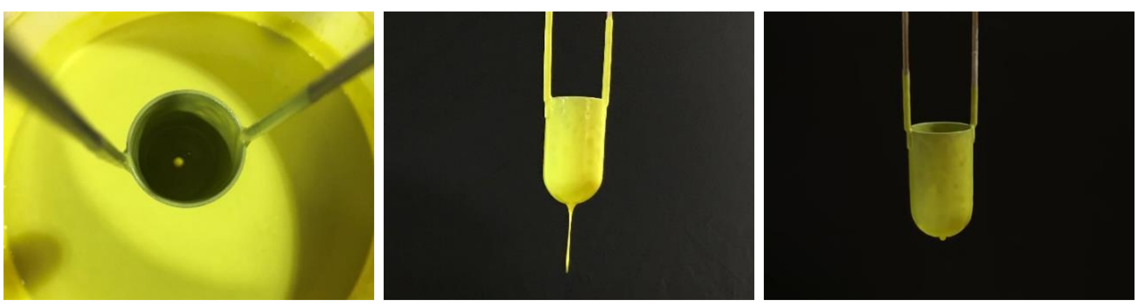
1. Insert a clean, dry flow cup into the fluid, filling the cup completely; then empty the cup. This step is often referred to as wetting the cup.
2. Reinsert the cup into the fluid.
3. Extract the cup and as the cup exits the top of the fluid, start a stopwatch.
4. Hold the cup vertically and observe the fluid.
5. Stop the stopwatch when the draining endpoint is reached.
6. Record the time.

This simple procedure is well suited for slurries used in the Precision Investment Casting (PIC) industry, as an operator or technician can simply take the flow cup directly to a slurry tank and easily measure the efflux time. In the PIC industry, the measured efflux time is accepted as representing the viscosity of the material even though it is not a cSt measurement. The viscosity measurement can then be compared to specifications. If viscosity doesn't meet specifications, the slurry can be adjusted back into range. Viscosity measurement is the most widely conducted test in the PIC industry.

In the PIC industry, every shell room is unique with regards to slurry formulations, part geometry, dipping technique and draining procedures. Because of this, it is possible that every foundry could maintain their viscosity within a range unique to them. The flow cup viscosity test is versatile enough to address all these specificities at a foundry, but universal enough to be a standard test.

There are several brands of standard dip style viscosity cups available, including EZ (Equivalent Zahn), Zahn Signature, Ford and ISO cups. Each of these cups come with various hole sizes in the bottom. For example, the Zahn Signature cups have 5 cups in the range (#1, #2, #3, #4 and #5). A larger number indicates a wider bottom hole diameter. The more viscous the material tested, the larger the hole should be in the cup. It is important to note that cups are not universally sized to a standard. #5 EZ and #5 Signature series cups will not give the same results when used to test the slurry.

In addition to the variation in readings based on the cup type and hole size, the endpoint, or when the stopwatch is stopped, also influences the viscosity reading. There are three endpoints for viscosity testing used in the industry, as shown in Figure 2: through the hole (TTH), one inch below (1 in) and break at the bottom (bottom).



Through the hole | One inch below | Break at the bottom

Figure 2

When using each of these endpoints, the viscosity is tested using the procedure above, but the endpoint (described in step 5) would be either through the hole, one inch below or break at the bottom. For the through the hole method, the operator looks down into the cup as it drains. Once the hole in the bottom of the cup opens and becomes visible, the endpoint is reached. When using the one inch below method, the stream of slurry exiting from the bottom of the cup is observed. As the cup empties, the stream will change.

When the stream turns from steady to droplets one inch below the cup, the endpoint is reached. The break at the bottom endpoint is reached when the stream of droplets is at the bottom of the cup.

Methodology

In preparation for this experiment, brand new Zahn Signature 5, EZ Zahn 5 and ISO Mini 6 viscosity cups were purchased to ensure the measurements taken would not be affected by an old cup worn down by use.

Two slurries were tested in this experiment: a polymer slurry and a polymer plus fiber slurry. Both slurries were built and maintained in a rotating tank. A detachable propeller mixer was used for two hours to aid in the make-up process. After initial make-up, the tank was covered and allowed to mix over the weekend.

Before beginning the viscosity measurements, ten readings were taken across the surface of the tank to ensure slurry homogeneity throughout. In order to consider a slurry homogeneous, all ten readings must fall within one second of each other. Without the propeller mixer on at a low speed, the slurry had a greater than one second variation between all ten viscosity readings. Because of this, the propeller mixer was running during all testing.

Once a slurry was stabilized, testing began. All readings were taken from the same location. Each operator was only told which viscosity cup and which endpoint to use for that test. The operator started and stopped the stopwatch for each viscosity measurement. However, they only showed the stopwatch to whomever was recording each data point so that they could not bias the readings. After the operator took their ten readings with that cup, they thoroughly washed the cup and the next operator took their measurements. This continued until all four operators had completed one endpoint with the cup, and then the rotation began again with the next endpoint until all for that cup were complete. When one cup was finished, the same process was repeated using a different viscosity cup.

Once all measurements were taken at a given viscosity, a liquid mixture of binder, concentrate and water was added in order to decrease the viscosity in set intervals and then left to mix for at least thirty minutes. This mixture was used in lieu of separate water and binder additions in order to maintain the same ratios in each slurry. Once the viscosity was considered stable again, the next set of viscosity measurements was taken. This process repeated until all five viscosity levels were measured with all cups and endpoints.

Using the Zahn Signature 5, EZ Zahn 5 and ISO Mini 6 cups, a total of 2800 viscosity readings were taken. The testing methods used on the Zahn Signature 5 and EZ Zahn 5 cups were industry accepted methods: through the hole, one inch below and break at the bottom. The only testing method used on the ISO Mini 6 cup was break at the bottom, as this is the only method recommended by the manufacturer. Four operators took ten readings at each loading with each cup and each method, resulting in 70 different variable combinations. This is summarized in Table 2.

Variables	**#**	**Comments**
Operator	4	
Cup	3	SIG, EZ, ISO
Endpoint	3	TTH, 1 in, bottom
Slurry	2	Polymer, Polymer plus Fiber
Loadings per Slurry	5	L1 (Thickest)…L5 (Thinnest)

Table 2

Results & Discussion

The readings from each variable were evaluated by their standard deviation to determine the precision of each operator, cup and endpoint. The cumulative viscosity reading time for the 2800 readings was nearly thirteen hours, with the fastest test at five seconds and the longest at thirty seconds. The data was used to create an averaged viscosity conversion chart between the three cups, as well as additional correlation charts between the Zahn Signature 5 and EZ Zahn 5 cups based on the endpoint being measured.

Operator

Tables 3 and 4, for polymer and polymer plus fiber slurries, respectively, show the deviation results by operator, cup and endpoint. Each individual operator had a relatively low deviation for their own readings, but the deviation was higher when readings from all four operators were compared. In practice, this would mean if operator 1 takes all readings in a consistent range, but operator 2 takes readings that all are 2-3 seconds higher, the deviation is high even though both operators were consistent on their own. This is the case in Tables 3 and 4 where operator average shows good agreement (precision) among the operators' individual measurements, but overall average of all readings across the operators shows more variation (accuracy).

In a foundry setting, these averages could be interpreted as follows:

- Operator average: One operator takes viscosity at the facility and is only compared to their other measurements
- Overall average: Three different operators take viscosity over three shifts at the facility and the operators are compared to the other operators' measurements

Operator Consistency (STD DEV): Polymer Slurry								
	SIG TTH	**SIG 1 Inch**	**SIG Bottom**	**EZ TTH**	**EZ 1 Inch**	**EZ Bottom**	**ISO Bottom**	**Operator Average STD DEV**
1	0.199	0.242	0.298	0.210	0.357	0.223	0.187	0.245
2	0.165	0.160	0.346	0.209	0.251	0.227	0.138	0.214
3	0.126	0.174	0.218	0.199	0.224	0.208	0.138	0.184
4	0.199	0.199	0.303	0.194	0.320	0.241	0.149	0.229
Polymer	**SIG TTH**	**SIG 1 Inch**	**SIG Bottom**	**EZ TTH**	**EZ 1 Inch**	**EZ Bottom**	**ISO Bottom**	
Operator Average	0.172	0.194	0.291	0.203	0.288	0.225	0.153	
Overall Average	0.232	0.305	0.435	0.342	0.475	0.463	0.222	

Table 3

Operator Consistency (STD DEV): Polymer plus Fiber Slurry								
	SIG TTH	**SIG 1 Inch**	**SIG Bottom**	**EZ TTH**	**EZ 1 Inch**	**EZ Bottom**	**ISO Bottom**	**Operator Average STD DEV**
1	0.353	0.737	0.440	0.365	0.852	0.699	0.241	0.527
2	0.276	0.368	0.373	0.284	0.502	0.409	0.292	0.358
3	0.300	0.456	0.445	0.394	0.496	0.484	0.268	0.406
4	0.315	0.315	0.387	0.600	0.565	0.494	0.258	0.419
Polymer plus Fiber	**SIG TTH**	**SIG 1 Inch**	**SIG Bottom**	**EZ TTH**	**EZ 1 Inch**	**EZ Bottom**	**ISO Bottom**	
Operator Average	0.311	0.469	0.411	0.411	0.604	0.522	0.265	
Overall Average	0.564	0.761	0.506	0.770	1.207	0.602	0.344	

Table 4

Endpoint

The data in Table 5 shows the deviations for all readings using each endpoint for the two slurries. Through the hole and break at the bottom were the most consistent methods tested, due to the definitive endpoint of the tests. The one inch below method has a subjective endpoint, resulting in higher deviations. Through the hole did have some subjectivity, though, but only at the highest viscosities with the polymer plus fiber slurry where the hole took much longer to open.

	Polymer Slurry Average	**Polymer plus Fiber Slurry Average**
TTH DEV	0.287	0.667
1 IN DEV	0.390	0.984
BOTTOM DEV	0.373	0.484

Table 5

For the foundry, this means that using a 1 inch below endpoint for viscosity on a polymer plus fiber slurry could introduce almost six seconds of deviation if viscosity is assumed as a normal distribution. This six second range is wider than the control range that most foundries use.

Cup

The precision of a flow cup is the ability to measure a viscosity consistently, while the accuracy of a flow cup is proximity of all readings to a target. Cup accuracy in this study was measured by the standard deviation of the readings of all operators with a given flow cup.

Table 6 shows the comparison in standard deviation between the polymer slurry and polymer plus fiber slurry across all three flow cups, regardless of operator or endpoint. For the polymer slurry, the readings by all four operators tended to stay much closer together, resulting in a lower overall deviation across cups. In comparison, the readings of the polymer plus fiber slurry were more spread out. The polymer plus fiber slurry was more difficult to determine the endpoint, especially with the one inch below and break at the bottom methods. This was due to the addition of fiber slightly changing the slurry rheology and ultimately affecting how the slurry acted as pressure dropped within the cup as it drained out. As a result, the cups were more accurate on the polymer slurry than the polymer plus fiber slurry.

The deviations for the Zahn Signature 5 and EZ Zahn 5 cups with the polymer plus fiber slurry are roughly double that of the polymer slurry. The ISO Mini 6 cup, however, only showed an increase of about 50%. This means that the ISO Mini 6 cup measurements showed greater accuracy over the other two cups, regardless of slurry type.

	Polymer Slurry Average	**Polymer plus Fiber Slurry Average**
SIG DEV	0.324	0.611
EZ DEV	0.427	0.860
ISO DEV	0.222	0.344

Table 6

For both slurries, there was much more difficulty determining the endpoint when the viscosity was higher. In general, there is a positive correlation between viscosity and deviations where the higher the viscosity, the higher the deviations and vice versa. As an example of this, Table 7 shows the deviations for the three cups over five loadings of the polymer plus fiber slurry.

	SIG Bottom	EZ Bottom	ISO Bottom
L1	1.061	1.220	0.373
L2	0.457	0.596	0.239
L3	0.493	0.615	0.381
L4	0.307	0.390	0.332
L5	0.214	0.189	0.397

Table 7

The range of deviations from the Zahn Signature 5 and EZ Zahn 5 cups across the loadings is more pronounced than with the ISO Mini 6 cup. Due to this, it will be more difficult to be accurate with the Zahn Signature 5 and EZ Zahn 5 cups at higher viscosities. On the other hand, the ISO Mini 6 cup is more consistent across a broad range, with the only exception being at the lower viscosities tested.

Conclusion

The data confirms industry perceptions that viscosity readings vary by operator, endpoint and cup. This evaluation assigned values, or relative values to variation caused by each of these variables.

In a foundry setting where multiple operators are taking viscosities on slurries, the ISO Mini 6 cup is the best option. It consistently had the lowest deviations amongst operators when compared to other cups. It also maintains a low deviation across the tested viscosity range. The low deviation allows the foundry to hold tighter viscosity because the deviation occupies less of the recommended slurry viscosity range than the other cups, resulting in both consistent and accurate measurements. An ISO Mini 6 cup is roughly 2-3 times more costly than a Zahn Signature 5 or EZ Zahn 5 cup. When a Zahn Signature 5 or EZ Zahn 5 cup is used, variation is reduced by employing the through the hole method.

Data showed a real-world difference between published viscosity equivalency charts and actual slurry viscosity correlations. The published chart is based on tightly controlled and calibrated oils, while this testing was conducted using ceramic slurries. Using gathered data, we produced more realistic equivalency charts for converting between different flow cups and endpoints. These charts are shown in Tables 8 and 9.

Correlation Charts

Polymer Slurry (seconds)				
SIG TTH	**EZ TTH**	**SIG Bottom**	**EZ Bottom**	**ISO Bottom**
30.00	27.96	30.06	37.54	34.56
29.00	27.52	29.13	36.38	34.01
28.00	27.06	28.20	35.22	33.45
27.00	26.59	27.27	34.06	32.87
26.00	26.10	26.34	32.90	32.27
25.00	25.59	25.41	31.74	31.65
24.00	25.07	24.48	30.57	31.01
23.00	24.51	23.55	29.41	30.34
22.00	23.94	22.63	28.25	29.64
21.00	23.33	21.70	27.09	28.92
20.00	22.70	20.77	25.93	28.16
19.00	22.04	19.84	24.77	27.37
18.00	21.33	18.91	23.61	26.54
17.00	20.59	17.98	22.45	25.67
16.00	19.81	17.05	21.29	24.75
15.00	18.97	16.12	20.12	23.78
14.00	18.08	15.19	18.96	22.75
13.00	17.11	14.26	17.80	21.66
12.00	16.08	13.34	16.64	20.50
11.00	14.95	12.41	15.48	19.25
10.00	13.71	11.48	14.32	17.90

Table 8

Polymer plus Fiber Slurry (seconds)				
SIG TTH	**EZ TTH**	**SIG Bottom**	**EZ Bottom**	**ISO Bottom**
30.00	37.90	31.43	36.07	34.28
29.00	36.66	30.48	35.04	34.34
28.00	35.43	29.53	34.01	34.31
27.00	34.20	28.58	32.97	34.20
26.00	32.97	27.63	31.93	34.01
25.00	31.74	26.67	30.88	33.72
24.00	30.51	25.71	29.83	33.35
23.00	29.28	24.74	28.78	32.89
22.00	28.05	23.77	27.72	32.35
21.00	26.82	22.80	26.65	31.71
20.00	25.58	21.82	25.58	30.97
19.00	24.35	20.83	24.51	30.15
18.00	23.12	19.84	23.43	29.23
17.00	21.89	18.85	22.34	28.21
16.00	20.66	17.85	21.25	27.09
15.00	19.43	16.84	20.15	25.87
14.00	18.20	15.83	19.04	24.55
13.00	16.97	14.81	17.93	23.12
12.00	15.73	13.78	16.80	21.58
11.00	14.50	12.74	15.67	19.92
10.00	13.27	11.69	14.53	18.15

Table 9

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