New Method for Accurate High Reynolds Metering Uses Water Calibration for Significant Cost Savings

White Paper

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White Paper

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1. INTRODUCTION

Cone meters have been shown to be an accurate measuring device for various flow applications. In order to maintain accuracy, Cone meters need to be calibrated to determine the discharge coefficient (Cd). The Cd often changes with Reynolds number. The same meter can have a different Cd for gas applications (high Reynolds numbers) than for liquid applications (low Reynolds numbers). Therefore a Cone meter needs to be calibrated over the entire range of Reynolds numbers for its specific application. In order to reach the high Reynolds numbers in most gas applications calibration need to be done in a gas lab. This often is verily costly and time consuming. To save time and money, accuracy is often sacrificed and a Cone meter slated for a gas application is calibrated in the manufacturer's water facility. McCrometer has developed a method that can predict the Cd at high Reynolds numbers based on a water calibration at small Reynolds numbers. This paper will discuss the accuracy of this method.

2. WATER CALIBRATIONS VS. GAS CALIBRATIONS

It is a well-known and understood fact that the discharge coefficient of any DP meter changes with Reynolds Numbers (Re). It is for this reason there are tables upon tables of Cd at different Re for orifice plates and the requirement for all Venturi meters in operation over Re 2,000,000 to be calibrated [1]. Cone meters have the same issue, requiring calibration for each meter produced. In theory, the meter should be calibrated over the full Re range of service to optimize accuracy. Figure 1 below shows a typical example of a Cone meter calibrated over a wide Re range. The Re range extends from 100,000 to 4,000,000 or a 40:1 turndown. As expected, the Cd increases as Re increases in the low and moderate range. As the Re increases further, the curve flattens, and Cd changes very little with respect to Re.

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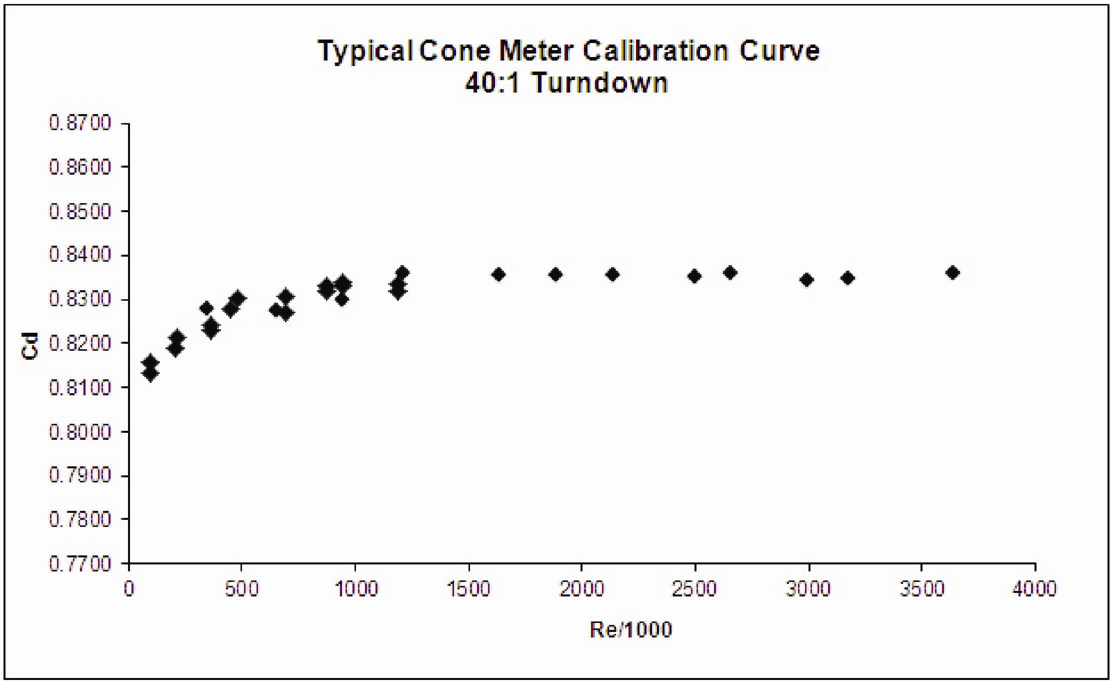

Fig. 1 – Typical V-Cone Meter Calibration Curve over 40:1 Turndown

In practice it isn't always possible or cost effective to calibrate over the full Re range. Water calibration, while common, can only reach so high. Even flowing at 40 ft/s (12m/s), a fast pace for a liquid, we can only achieve moderate Re. For applications in gas where Re can be much higher, gas calibration would be needed to cover the complete Re range. This presents a problem. Gas calibration is expensive, and can in some cases double the total cost of the instrument. In addition, there are only a limited number of gas calibration labs in the world. With their time in high demand, scheduling problems often arise causing delays in delivery. In many cases, the accuracy requirements of the application are between +/-1% to 2% so ultra-high accuracy metering (+/-0.5% or better) is not needed. For these reasons, the majority of gas Cone meters are water calibrated only with a stated accuracy of +/-1 to 2%.
There are some skeptics that don't believe this is a good practice and advocate that one doesn't know the performance curve of a meter unless it is calibrated over the full Re range siting that while the Cd changes little with respect to Re, it does still change. Therefore a proven system to predict the Cd at higher Re ranges is necessary to settle fears that a meter is still accurate in gas but calibrated in water. Ideally this system could predict the Cd within +/-1% of the actual value at ranges above what can be achieved in water alone.

McCrometer has developed such a prediction method. It is intended to use water calibration data alone to predict the Cd vs. Re flow curve at higher Re not covered by the water calibration. The details of the method remain the intellectual property of McCrometer and will not be discussed in this paper. However the predicted Cd and accuracy as compared to gas tests will be shown.

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3. API 5.7 BASELINE TESTING

In 2003, the American Petroleum Institute launched protocol 5.7. The aim for API 5.7 was to either prove or disprove the claims different Differential Pressure metering devices not covered by AGA or ISO standards. In doing so they would establish standard tests each manufacturer would perform so that end users could make an informed decision on meter accuracy and repeatability. For the purposes of this paper we will review the baseline tests for the V-Cone flowmeter.

Figure 2 shows the calibration results in both water and gas for a 4" 0.45 Beta ratio V-Cone. Gas calibration was performed at South Western Research Institute (SWRI). Natural gas was used as the process fluid.

Over the Re range where data was taken for water and gas, the calibration results overlapped within experimental error. As seen in Figure 1, the Cd vs. Re profile flattens as Re increases. In addition to the raw data, McCrometer prediction method has been overlaid. The error bars in all subsequent figures represent a shift +/-1% from the prediction to the actual test data.

The results are very good. Each point predicts the Cd within approximately 0.5% to Re 5 times higher than the maximum water data point.

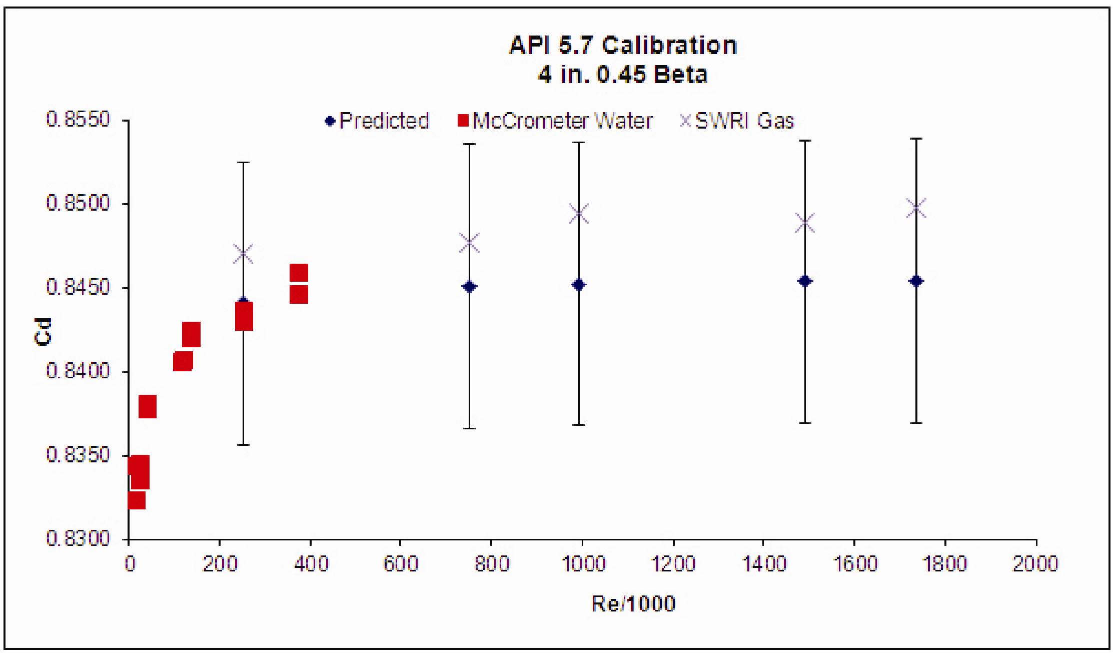

Fig. 2 – API 5.7 Water and Gas Calibration for a 4 in. 0.45 Beta V-Cone Meter

To ensure the 0.45 beta cone was not a "sweet spot" for a 4" size, an additional 0.6 and 0.75 beta V-Cones were tested. Figure 3 shows the Cd vs. Re for the 4" 0.6 beta V-Cone. In addition to repeating the test points as was done with the 0.45 beta cone, the 0.6 beta V-Cone was calibrated up to a max Re 11,000,000 or 15 times higher than the max water data point. Even at 15 times higher Re, the Cd was predicted to within better than 1% from the test point.

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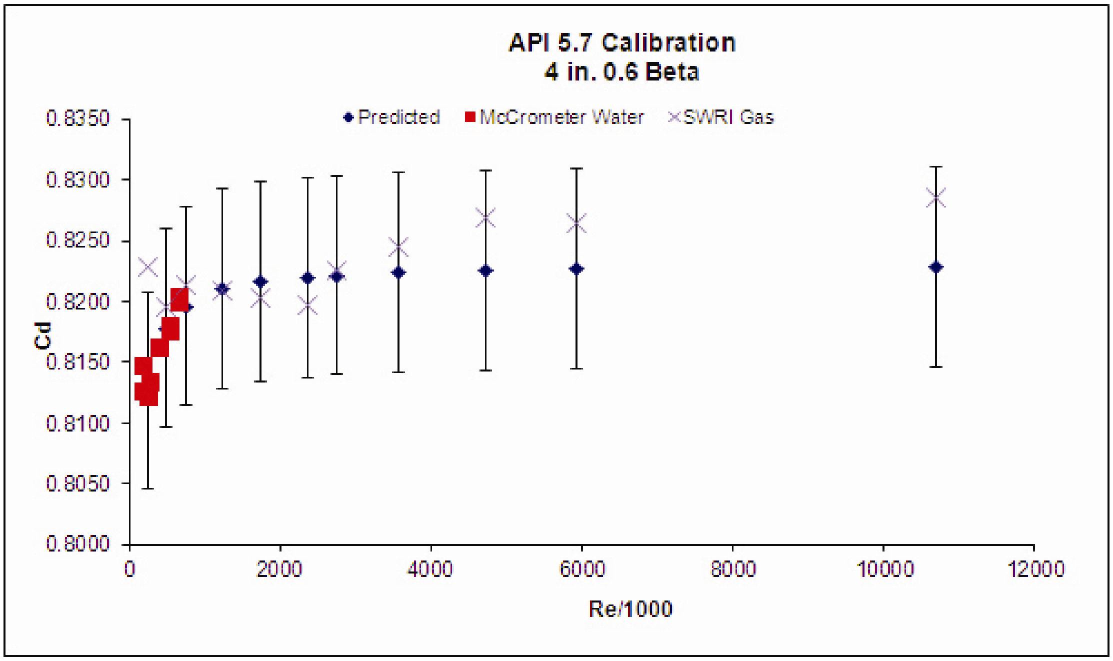

Fig. 3 – API 5.7 Water and Gas Calibration for a 4 in. 0.6 Beta V-Cone Meter

Figure 4 shows the results of the 0.75 beta ratio cone. The predicted Cd compared to the tested Cd again was found to be less than 1% different. An interesting find with this test set was that the gas data was found to be below the prediction horizon whereas in the previous 2 sets of data show the gas data above the prediction horizon.

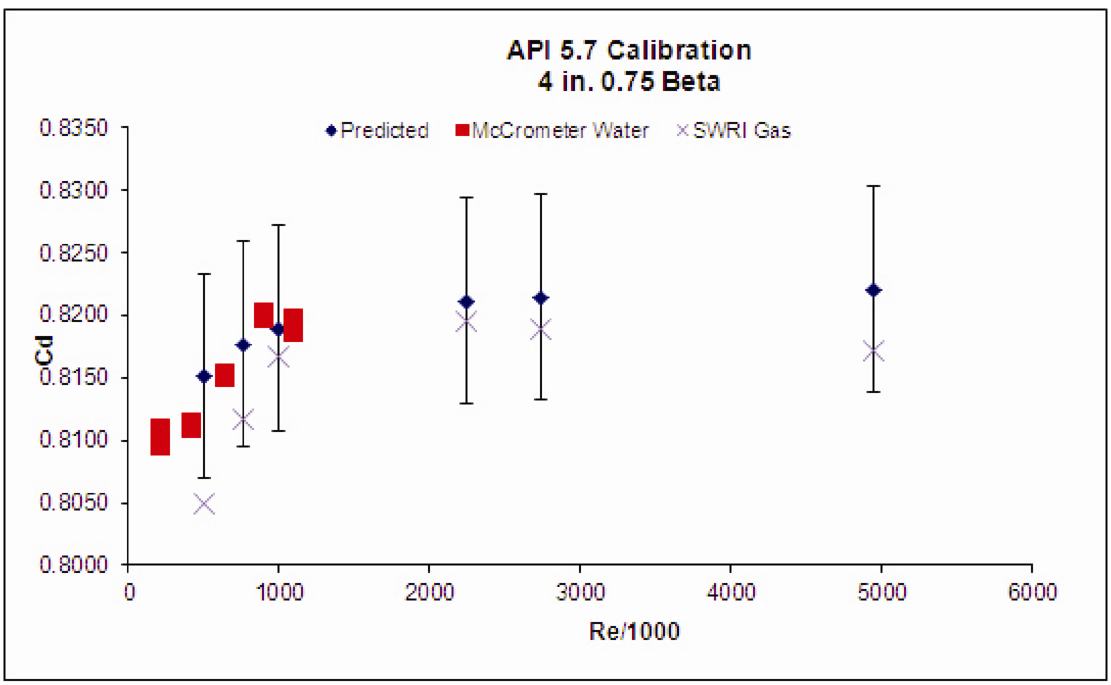

Fig. 4 – API 5.7 Water and Gas Calibration for a 4 in. 0.75 Beta V-Cone Meter

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Per API 5.7, 2 line sizes must be tested. The sizes must have a 2:1 nominal ratio so to meet the requirements of 5.7, an 8" V-Cone must be tested in addition to the 4". Figure 5 shows the results of the 8" 0.75 beta V-Cone. Similar to the 4" 0.75 beta V-Cone in Figure 4, the gas was within 1% of the predicted Cd at a range 5 times higher than the max water point and the data is slightly under the prediction horizon.

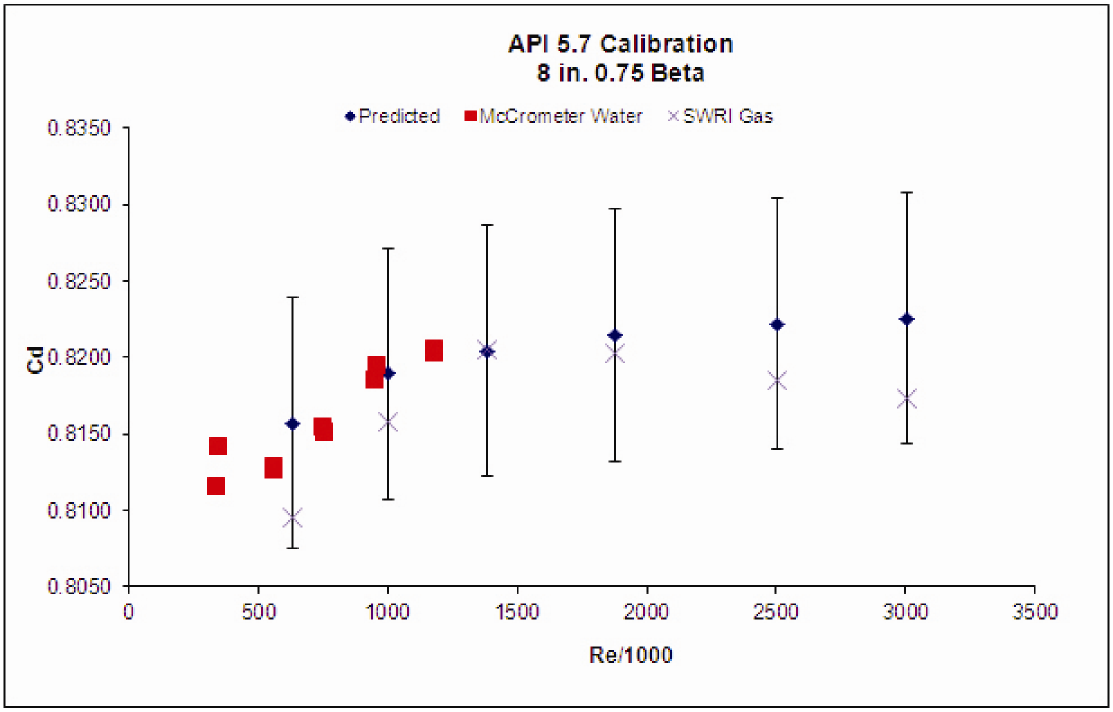

Fig. 5 – API 5.7 Water and Gas Calibration for an 8 in. 0.75 Beta V-Cone Meter

Based on the API 5.7 baseline tests the Cd prediction method for high Reynolds numbers looks very good. Almost all points are within +/-1% for Reynolds numbers up to 15 times greater than the water calibration Reynolds number.

4. API 22.2 BASELINE TESTING

In January of 2005, API released a revision of 5.7 and re-designated the standard 22.2. This testing protocol included additional testing on top of what was required by 5.7. For the purposes of this paper we will examine the baseline testing only [2]. Testing to API 22.2 was undertaken at CEESI Colorado and was done in air instead of natural gas. This study included the air data from the API 22.2 testing because it was conducted on a different gas than the 5.7 tests to investigate if the prediction method is gas dependent, another potential "sweet spot."

Figure 6 shows the 22.2 test results for an 8" 0.75 beta ratio V-Cone. The gas test points almost match exactly the predicted Cd values at 3 times higher than the max water data. Water and gas data also overlap almost identically. Predominately, the gas data points were slightly above the prediction horizon, just the opposite from the 8" 0.75 beta V-Cone tested to 5.7.

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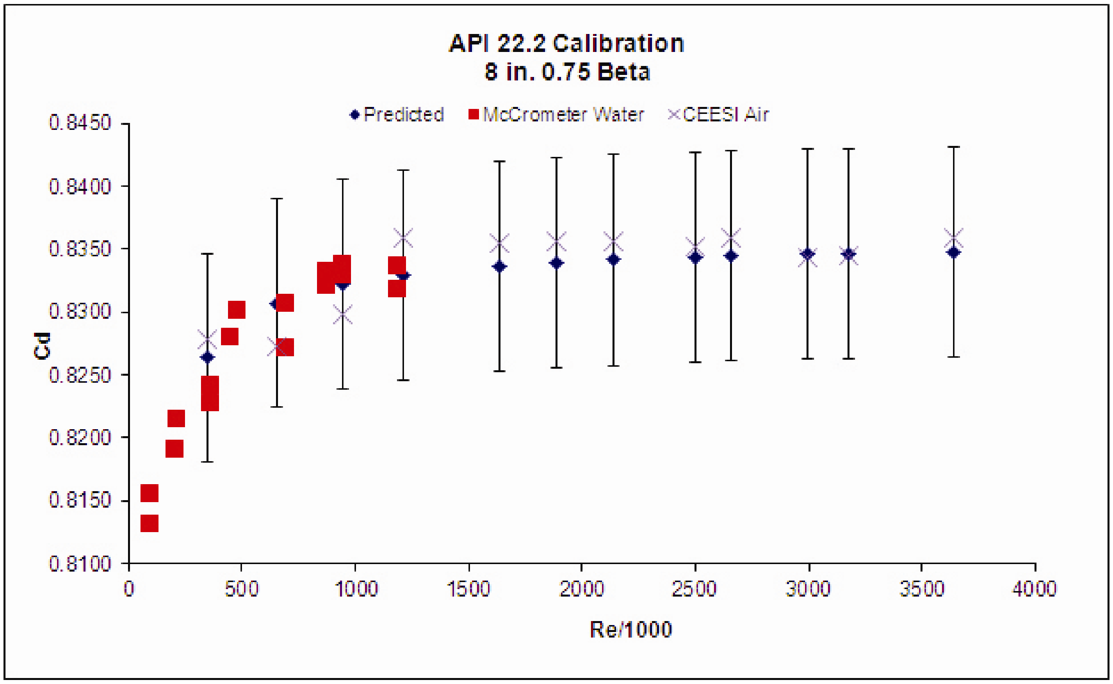

Fig. 6 – API 22.2 Water and Air Calibration for a 8 in. 0.75 Beta V-Cone Meter

Figure 7 shows the 22.2 calibration results for a 4" 0.75 beta ratio V-Cone. At 2 times the max water data the predicted Cd is just over 1% lower than the gas data points. The data was predominantly above the prediction horizon the same as the 5.7 tests.

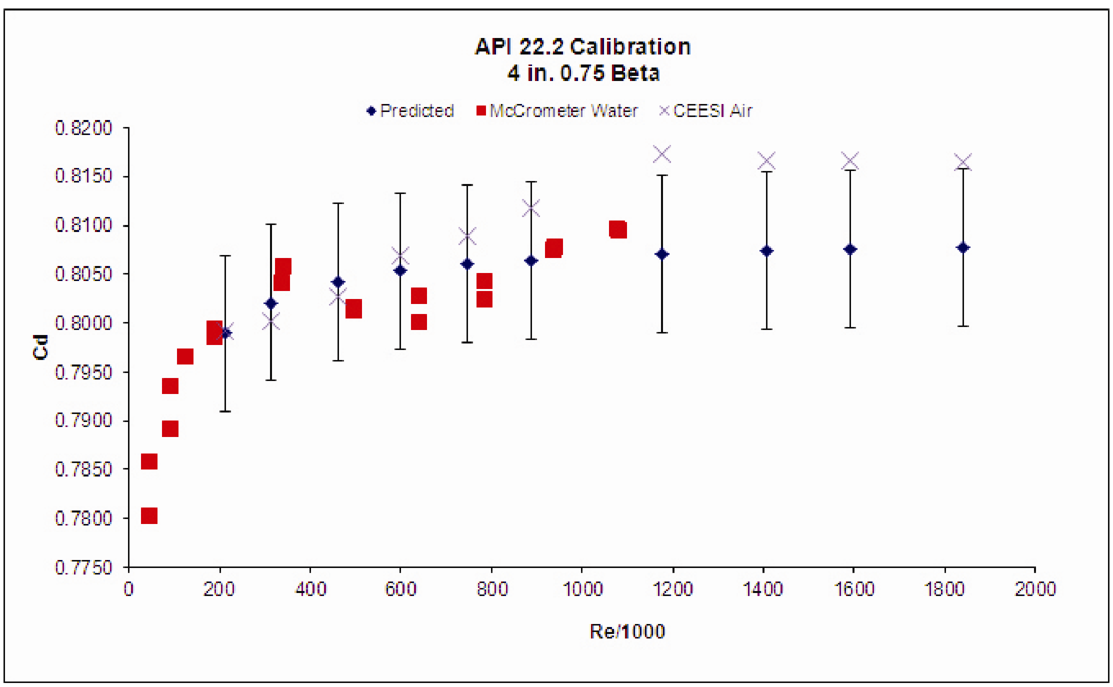

Fig. 7 – API 22.2 Water and Air Calibration for a 4 in. 0.75 Beta V-Cone Meter

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Figure 8 shows the 22.2 calibration results of a 4” 0.45 beta ratio V-Cone. At 10 times the maximum water test point, the predicted Cd was within 1% of the gas data. All gas data was above the predicted horizon.

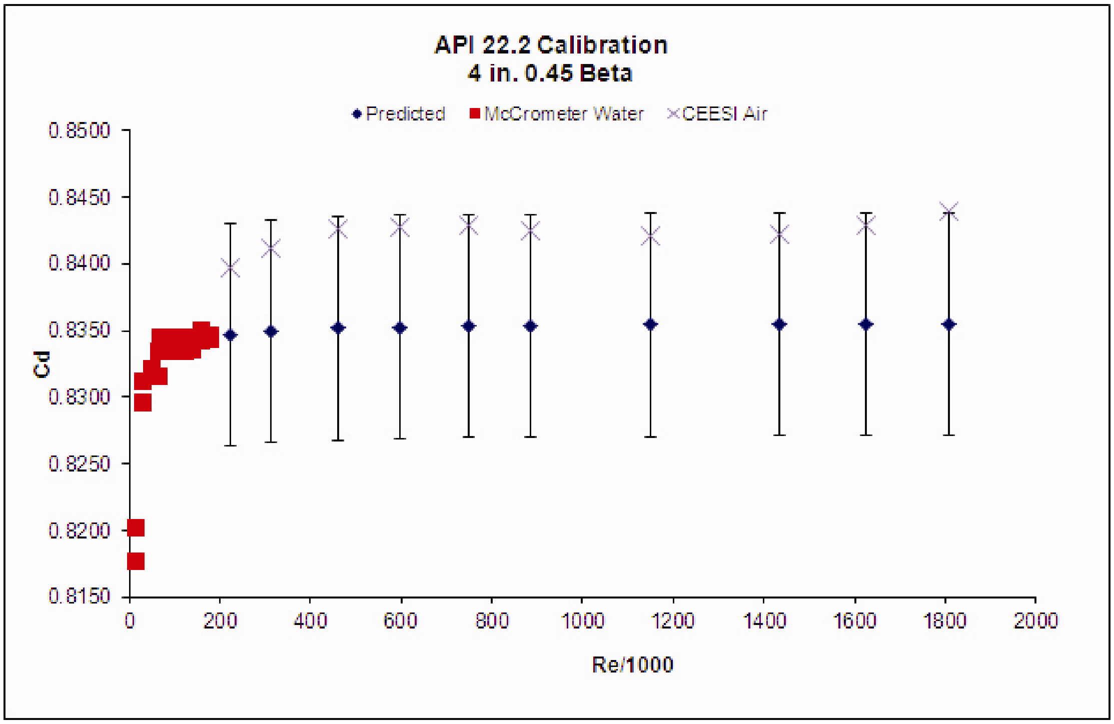

Fig. 8 – API 22.2 Water and Air Calibration for a 4 in. 0.45 Beta V-Cone Meter

In addition to 4” and 8” meters, testing to API 22.2 included 2” V-Cones of different beta ratios. Figure 9 shows the 22.2 calibration data for a 2” 0.45 beta ratio V-Cone. At 3 times higher Re from the max water data the predicted Cd is less than 1% lower than the gas data. All gas data was above the predicted horizon.

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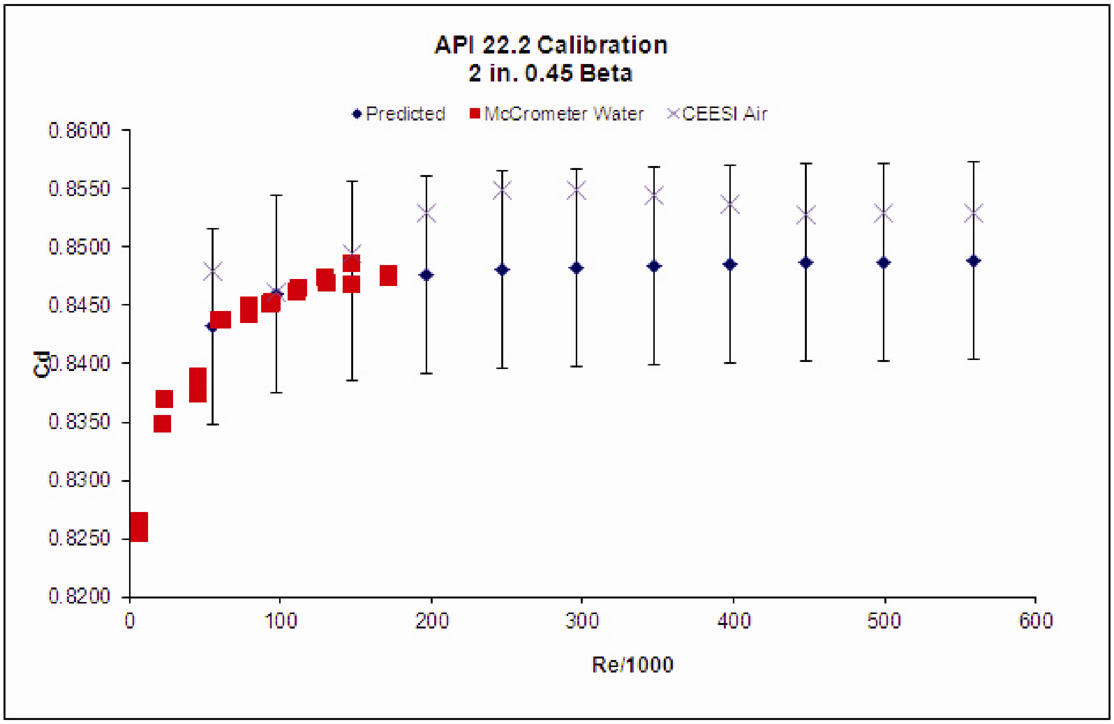

Fig. 9 – API 22.2 Water and Air Calibration for a 2" 0.45 Beta V-Cone Meter.

Figure 10 shows the 22.2 calibration of a 2" 0.75 beta ratio V-Cone. At 6 times higher than the max water data point the predicted Cd is within 1% of the gas data. Predominately the gas data is below the predicted horizon.

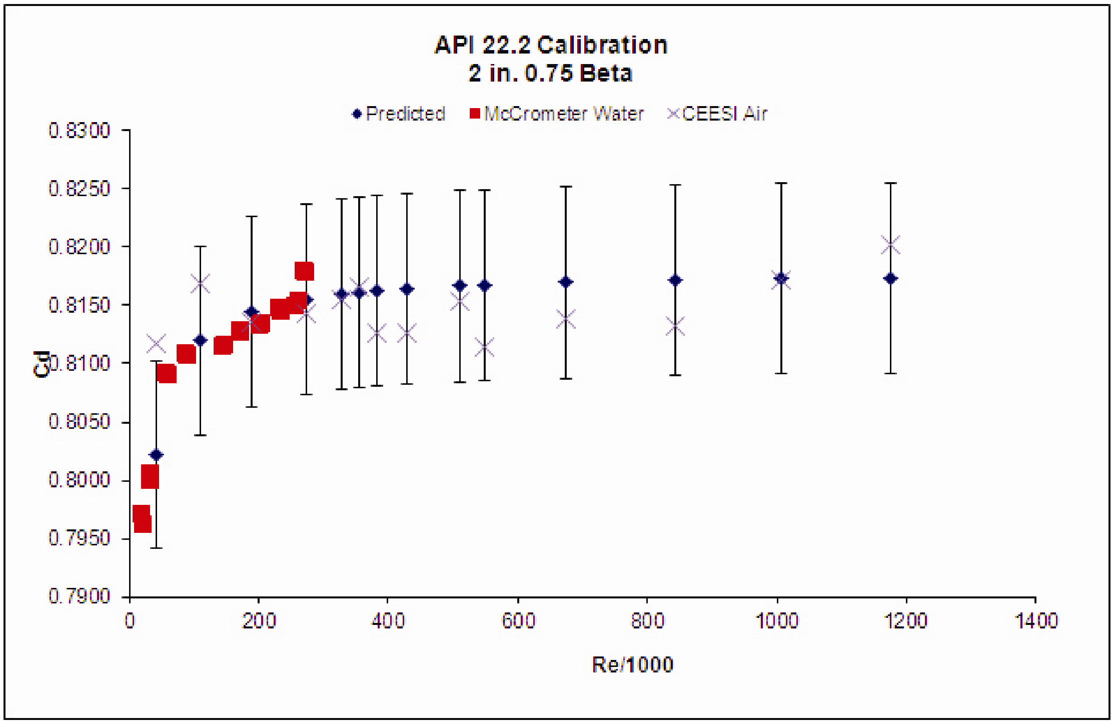

Fig. 10 – API 22.2 Water and Air Calibration for a 2" 0.75 Beta V-Cone Meter.

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The API 22.2 baseline results are similar to the 5.7 results. The prediction method works very well. Nearly all points are within +/-1% for Reynolds numbers up to 10 times greater than the water calibration Reynolds number.

5. METERS TESTED IN MCCROMETER AIR LAB

McCrometer has operated a small air test stand for several years and can be used to test V-Cones from 0.5" to 2" in moderate air flows. While modest, it can still achieve Reynolds Numbers higher than can be produced in water alone and is a useful tool in testing theory.

Figure 11 shows the results of a 0.5" 0.65 beta ratio V-Cone tested in McCrometer's air and water tests stands. Over the Re range where the meter was tested in both water and air the data sets are within experimental error. Up to 4 times higher than the max water data point the predicted Cd is within 1% of the gas test. The gas data is evenly distributed above and below the predicted horizon.

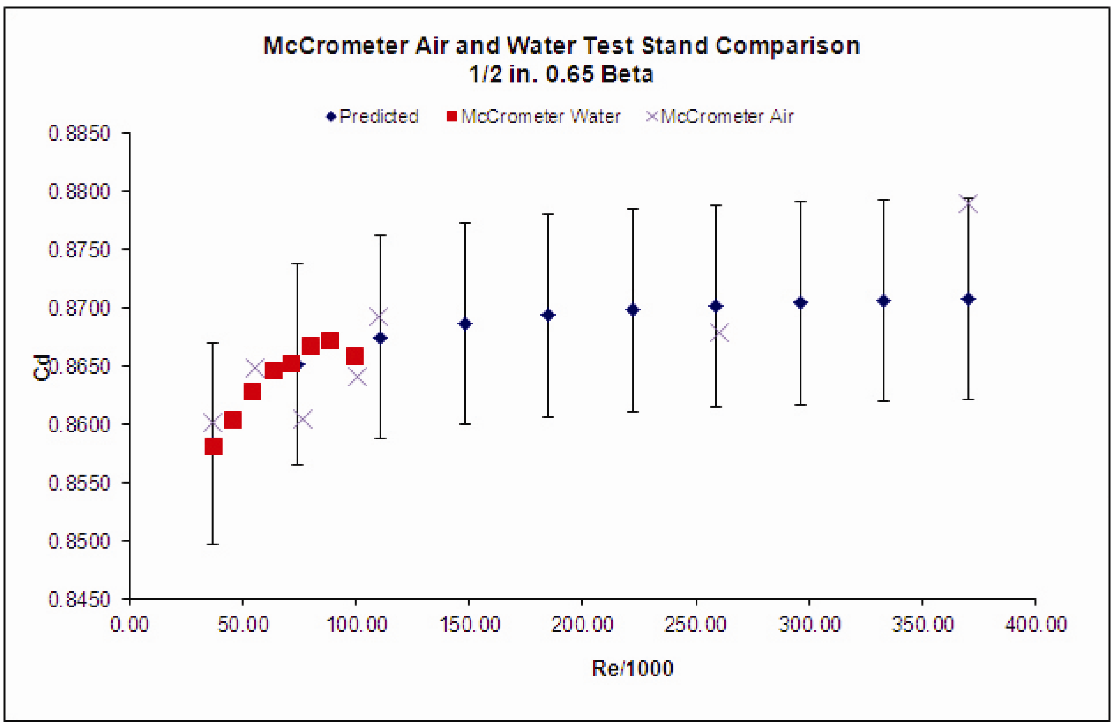

Figure 11 – McCrometer Air and Water Test Stand Comparison for a ½" 0.75 Beta V-Cone Meter

Additional meters have been tested in McCrometer's air and water labs. Further results are summarized with other meters in the next section.

6. OVERVIEW OF VARIOUS TESTS

To further test the theory that a method could be used reliably to predict the Cd within +/-1%, 20 V-Cones, including many production meters, were calibrated in gas as well as in water. These ranged in size from 0.5" to 14" and beta ratios from 0.75 to 0.45, with calibrated Re ranges from 37,000-370,000 for the small V-Cones, to 1,600,000-7,200,000 for the larger diameter V-Cones. In addition to the calibration in McCrometer's water lab, the production meters were tested at

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SWRI, CEESI Co or in McCrometer's air lab. Figure 12 below shows the error of the predicted Cd for each test point of the various meters vs. the Reynolds number magnitude increase over the water Reynolds number.

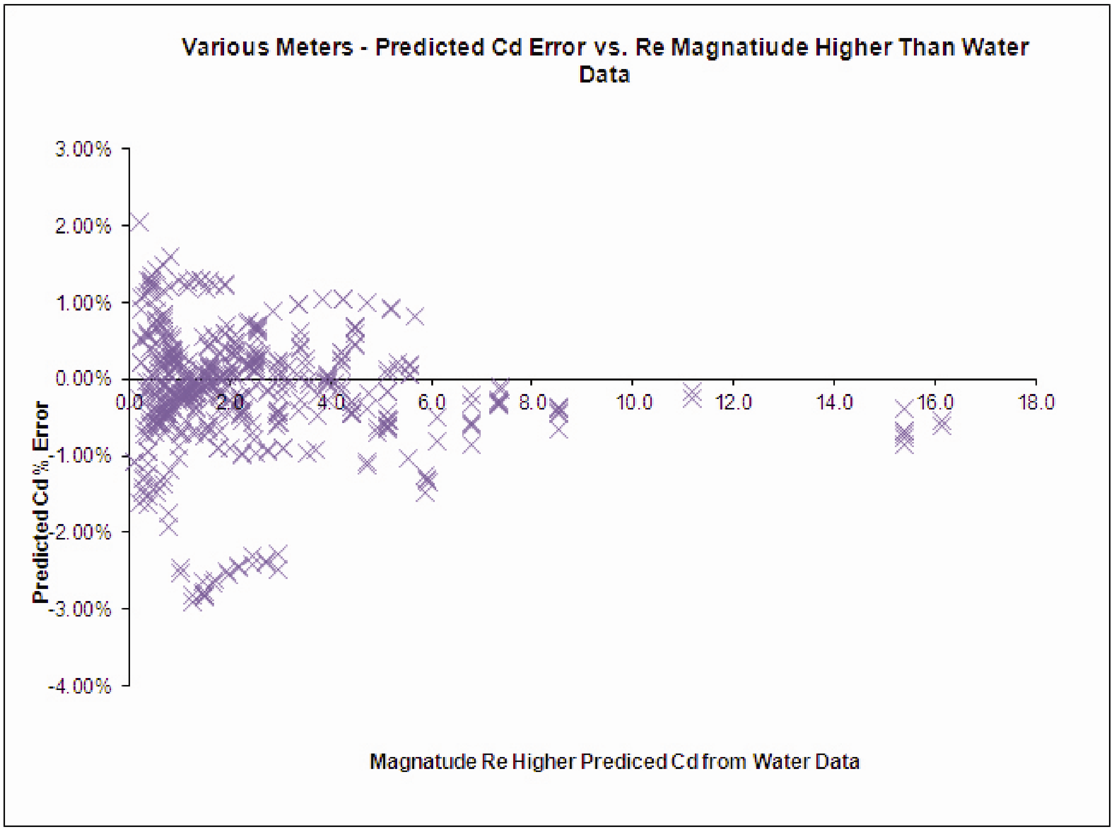

Figure 12 – Summary of the accuracy of the prediction method for various meters and test points.

Most of the test data shows very good results, clustering around +/-1%. The error can reach as high as +2% and as low as -3%. Table 1 summarizes the results of each meter that is shown in Figure 12.

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Table 1 – Summary of Prediction Method accuracy for Each Meter

Meter Size	Beta Ratio	Max Error	Min Error
0.5	0.65	0.59%	-0.93%
0.5	0.56	-0.40%	-0.98%
0.5	0.49	0.24%	-0.27%
0.5	0.46	1.05%	-0.59%
0.5	0.45	2.06%	-0.68%
0.5	0.45	1.59%	-0.25%
2	0.47	0.34%	-1.03%
2	0.44	0.53%	-0.16%
3	0.70	0.22%	-0.70%
4	0.75	1.36%	0.06%
4	0.75	-1.38%	-2.91%
4	0.60	0.63%	-1.64%
4	0.50	-0.18%	-1.60%
4	0.45	0.36%	-0.35%
4	0.45	-0.17%	-0.65%
8	0.75	1.07%	-0.18%
8	0.60	-0.05%	-1.47%
10	0.55	0.22%	-0.62%
12	0.72	0.34%	-0.81%
14	0.69	0.57%	-1.37%

One 4” 0.75 beta V-Cone in this study did not present the same results as the rest of the meters. Figure 13 shows the calibration results for this V-Cone. The gas results show a gas Cd curve shifted significantly higher outside the +/-1% exhibited by the other 19 production V-Cones. The gas data and water data overlap at Re 260,000 to 850,000. At Re 260,000 the gas data Cd is 1.5% above the water data for the same Re. The delta between the 2 sets of data increases to 2.8% at the max water Re data point, and up to 3.25% at the maximum delta between the prediction horizon and gas data (Approximate Re 1,065,000).

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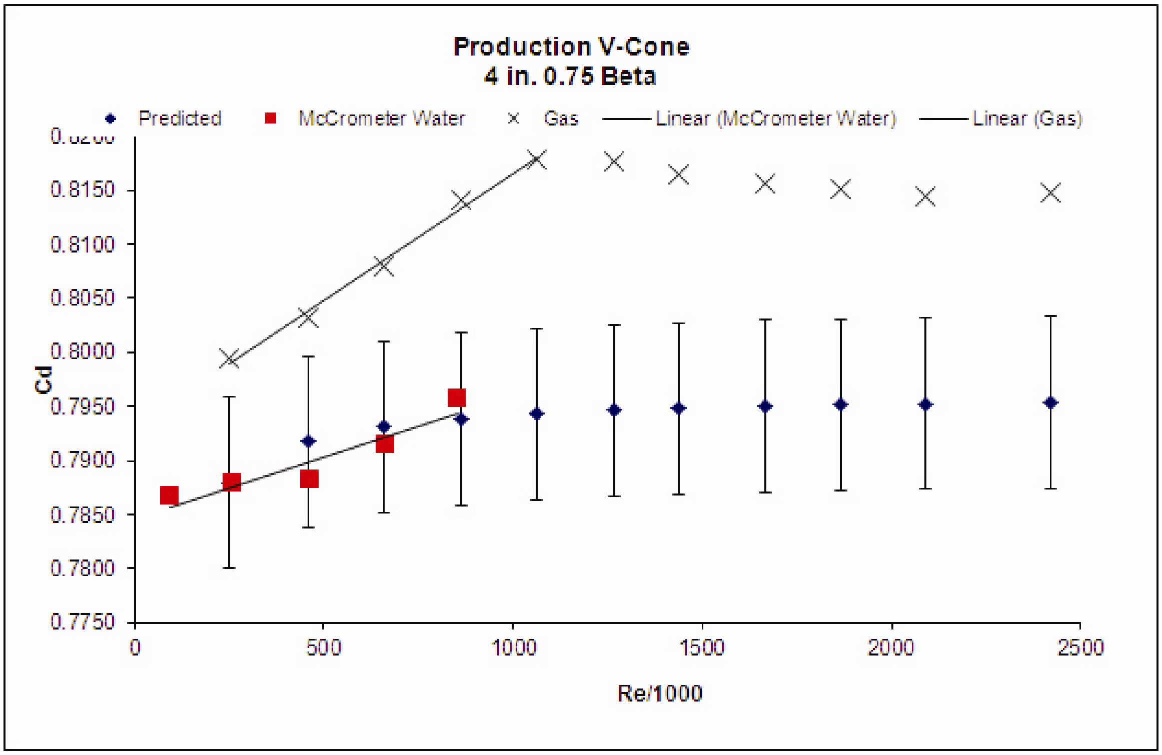

Figure 13 – Production V-Cone 4in 0.75 Beta Ratio

While the exact reason for the delta cannot be determined by statistical analysis alone one can make assumptions of what might cause the delta. Generally this occurs when one or both sets of data are flawed. Both sets of data present steady increases in Cd. The water data has a distribution of Cd between 0.7870 and 0.7960 or an overall change of 1.1%. The gas data has a distribution of Cd between 0.8000 and 0.8180 or an overall change of 2.3%. The slope of the change of Cd in the gas data being 2x the slope of the same water data indicates a problem with the gas data. Causes of flawed gas data include:

- DP Transmitter has fallen out of calibration or operated outside of the optimum scale range
- DP Transmitter is not zeroed correctly
- Transfer standard is out of calibration or operated outside of the optimum scale range

Even with the poor results from this meter the overall accuracy of the prediction method is very good. The mean error for all of the test points is -0.17%. This shows that the prediction method has little to no bias. The Standard Deviation for all of the test points is 0.81%. This allows us to say with a 95% confidence level that even with differences between flow labs the prediction method is easily within +/-2%. If we incorporate the differences between labs the prediction method can be within +/-1%.

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7. CONCLUSIONS

Based on the sampled data the prediction method works very well. Overall average uncertainty of 1.62% at the 95% confidence level shows us that even with the shift between flow labs our assumption of 1% uncertainty for the prediction method close. Calculating that the labs have a small shift we can say that the accuracy is +/-1%. The original assumption was that the prediction method would be valid for Reynolds numbers up to 10 times greater than the maximum water Reynolds number tested. Results show that the method is good up to 16 times the tested Reynolds number. It seems likely that even higher Reynolds number predictions would be accurate, but we do not currently have data to support this claim. Eight different sizes from 14 inches down to 0.5 inches were tested and the results show no dependency on diameter. Various beta ratios were tested from 0.75 to 0.45 and the test results show no cone diameter (beta ratio) dependency. The gas tests were performed in 2 different fluids, air and natural gas, the test results show that, other than Reynolds number, no dependency was found on the type of gas tested.

In some of the figures the predicted Cd values appear to simply be the water calibrated Cd at the highest Reynolds number. This is because the water calibration is able to reach Reynolds numbers where the slope of the Cd vs. Re curve is near zero. One cannot make this assumption for all cases. The prediction method discussed in this paper does not make this assumption and has been shown to accurately predict the high Reynolds number Cd values even when the slope of the water calibration curve is not near zero (see figure 3).

While this method has been shown to be statically viable, and McCrometer has started to use it in its calibration process, the results are not flawless. McCrometer will continue to gather data for meters that are tested in gas labs and refine the process when necessary. Ideally the method could be refined to achieve an uncertainty of +/-0.5% with a 95% confidence level. We are also interested in expanding the method to low Reynolds numbers for highly viscous applications.

8. NOTATION

Cd	Discharge coefficient of a meter
Re	Reynolds Number
β	Beta Ratio

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[1] International Organization for Standards. ISO/FDIS 5167 Measurement of fluid flow by means of pressure differentia devices inserted in circular cross-section conduits running full. Part 4: Venturi tubes. 2003.

[2] American Petroleum Institute. Manual of Petroleum Measurement Standards, Chapter 22 – Testing Protocol, Section 2 – Differential Pressure Flow Measurement Devices. First Edition, August 2005.

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