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Autonomous ICD Single Phase Testing

Brandon Least, Stephen Greci, Halliburton; Russell Burkey, Adam Ufford, Angel Wileman, Southwest Research Institute

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Abstract

Reservoir flow control is important for maximizing hydrocarbon production. Traditional in-flow control devices (ICDs) attempt to balance the completion pressure differential with the reservoir pressure differential so that even flow across production zones is maintained. This maximizes oil production by delaying unwanted fluids from breaking through. Unfortunately, when lower viscosity fluids do break through, they take over the well, significantly reducing production of the desired hydrocarbon. This paper describes the design and function of a new self-adjusting in-flow control device (AICD). When hydrocarbons are producing from all zones, the AICD will behave as a traditional ICD, balancing flow. However, when low-viscosity fluids break through, the AICD chokes them, significantly slowing flow from the zone producing the undesirable fluids. This autonomous function enables the well to continue producing the desired hydrocarbons for a longer time, maximizing total production.

The paper describes the laboratory testing performed to evaluate the performance of the new AICD in field-like conditions. Results from single phase experimental flow testing with model fluids are presented and discussed.

The testing results proved that the AICD could restrict flow from zones producing undesirable fluids. The discussion further shows that if technology such as the new AICD is applied to new well completion designs, total hydrocarbon recovery will be enhanced, providing a significant benefit for production companies and those involved in design and modeling of new well completions.

INTRODUCTION

A common method of maximizing contact with the pay zone of a narrow oil-bearing formation is by creating horizontal well bores. Advances in directional drilling make this well configuration possible, but with this new method of completion, also comes challenges. One of these challenges is the uneven production of fluid along the length of the completion. This uneven production occurs both in long homogeneous completions, in which fluid tends to enter the heel much faster than the toe, and in heterogeneous formations in which fluid travels much more rapidly through the more permeable rock than the less permeable rock. This uneven production of fluid leads to the breakthrough of undesired, more mobile fluids such as water and/or gas. Once these fluids break through, they tend to take over the well, significantly reducing the production of oil. The industry has combated this problem by installing passive inflow control devices (ICDs). ICDs create an additional pressure drop in the well which serves to balance the inflow of fluids along the length of the well, delaying the onset of undesired fluid breakthrough. Although passive ICDs help delay this breakthrough, once breakthrough occurs they have no capability to slow down this production of undesired fluids. (Dikken, 1990) (Brekke and Lein, 1994)

The Autonomous ICD (AICD) was developed specifically to combat these common long horizontal completion issues. The AICD is a next generation ICD that not only functions as a passive ICD, but can also significantly reduce the production of undesired fluids once breakthrough occurs. This reduction in undesired fluids occurs autonomously, utilizing innovative dynamic fluid technology in order to differentiate between the desired and undesired fluids. **Figure 1** shows a comparison of a passive ICD and the AICD. The AICD does not have any moving parts, does not require downhole orientation, and contains no elastomeric seals. This results in a simple, reliable, and cost effective solution to the known limitations of passive ICDs. (Birchenko et.al, 2008)

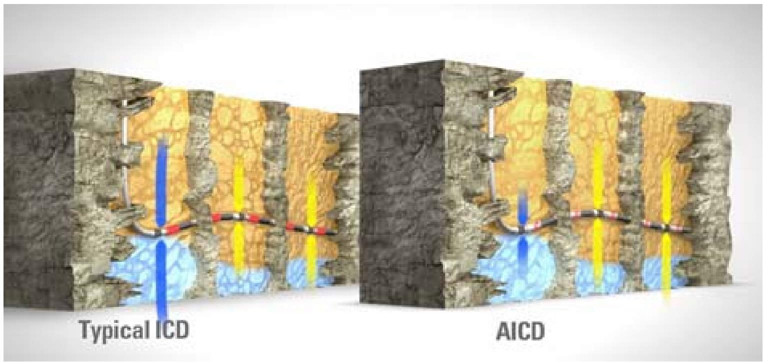

Figure 1. Flow rate representation of water through a typical ICD and that of an AICD after breakthrough

The Autonomous ICD is a solid-state valve that allows the flow of desirable fluids, like oil, and restricts the flow of undesirable fluids, like water. The AICD provides two main functions, the viscosity selector that identifies the fluid and the flow restrictor that restricts the flow when undesired fluids are present. Both of these functions are created by specially designed flow channels inside of the solid carbide valve.

The oil, being more viscous, tends to take the shortest path to the exit, entering the exit nozzle radially. This direct pathway results in minimal flow restriction for the oil. The water, being less viscous, tends to bypass the channels leading directly to the exit nozzle and instead, is put on a tangential path to the exit nozzle. This tangential path causes the water to begin spinning rapidly as the water nears the exit nozzle. This rapid spinning creates a large pressure drop, significantly reducing the flow rate of water (undesired fluid) through the device.

Figure 2. Complete AICD valve shown.

Figure 2 is a picture of the palm-sized device, constructed out of a solid piece of tungsten carbide. The valve is mounted in a housing that attaches on the outside of a standard base pipe. The compact size allows for a low profile construction with no protrusion to the inside of the base pipe. The number of valves utilized is based on the user requirements and can also be easily adapted to attach to a screen. **Figure 3** illustrates an AICD assembly (cover sleeve that directs flow from the screen to the valve has been removed for clarity).

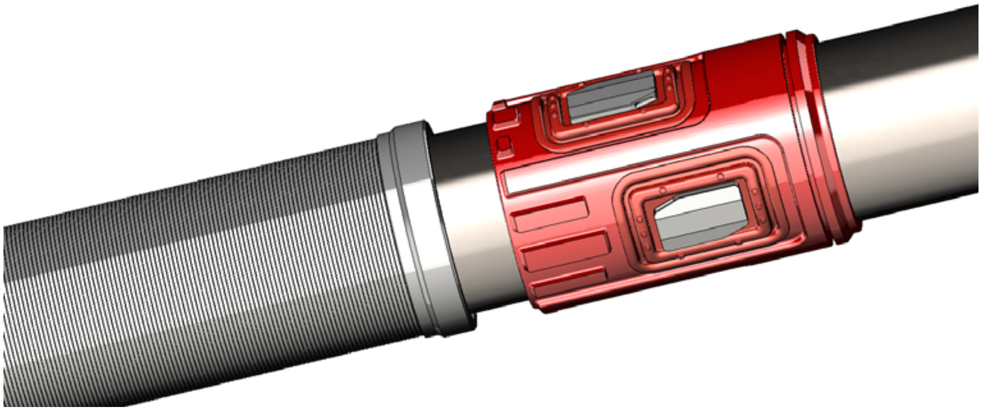

Figure 3. AICD installed on a base pipe with a screen section (cover sleeve removed)

The flow channels inside of each AICD were optimized for a specific range of fluid viscosities. The Range 3 and Range 4 designs are discussed in this paper and have been tested from 3 cP to 1000 cP. The data presented below is a global snap shot of the performance of both devices in single-phase flow.

EXPERIMENTAL METHODS

The testing was conducted in a dedicated flow facility that was set up to test the AICDs. A simplified schematic showing the main components of the test setup may be found in **Figure 4**. **Figure 5** shows a photograph of the test setup.

The test setup included a single triplex pump connected to an open tank containing oil or water providing the flow in a recirculating loop. The pump was equipped with a variable frequency drive (VFD) and a bypass on the pump discharge returning to the tank to control the upstream pressure at the test article and total liquid flow rate.

The AICD inserts were contained in a short (~4-ft overall length) test article that mimics the installation of the AICD tool in the well. The test article was fabricated using 5.5-in. 17 lb base pipe with a 12-in., open-ended 16-gauge (400-micron) screen section. The test articles contained an ICD housing section in which one AICD insert per test article was installed. Note the number of AICD inserts per housing can be varied in order to accommodate expected reservoir conditions. The flow rate for a single insert AICD can be scaled according the number of desired inserts for a given pressure differential. For example, if pressure differential Y and flow rate X are known for a single insert AICD tool, then the expected flow rate for a three insert AICD tool would be 3*X at pressure differential Y.

The AICD test article was contained within a test fixture which was oriented horizontally and positioned such that the single insert was oriented downward. Fluid flow was directed to an annulus between the test fixture ID and test article base pipe OD, through the screened section, through the AICD inserts, and into the base pipe ID. The test fixture was ported in order to measure the pressure directly upstream (i.e., the annulus between the well bore and production tubing) and downstream (i.e., inside the production tubing) of the AICD housing section.

As shown in Figures 4 and 5, the test facility was configured to accommodate two test fixtures and test articles in parallel in order to more efficiently complete the test matrix for the Range 3 and Range 4 AICD test articles. The test facility contained manual block valves upstream and downstream of each test fixture so that the flow was directed though only one ICD at a time.

In order to achieve the wide range of fluid viscosities required by the test matrix, five different paraffinic base oils were used as the test fluids. Prior to testing, the fluid kinematic viscosity as a function of temperature for each test oil was measured using a laboratory viscometer in accordance with ASTM D-445. In addition, the fluid density was measured in accordance with ASTM D-4052 and the dynamic viscosity as a function of temperature was calculated. During testing, dynamic viscosity of the test fluid in the loop was determined by measuring the temperature just upstream of the test fixture and interpolating within this viscosity as a function of temperature data. The test fluid temperature was controlled with a shell and tube heat exchanger, supplied with either heated or chilled water, installed in the return side of the flow loop. In addition, most of the test facility flow lines and test fixture were insulated in order to help control temperature. Each oil was loaded individually into the flow loop. Preceding oils were completely drained and flushed before the subsequent oil was loaded.

The test facility was instrumented to measure the flow rate, the static pressure and temperature at the inlet and outlet of the test article, and the differential pressure across the AICD test article. The total liquid flow rate was measured with a Coriolis flow meter. All instruments used in the test facility are calibrated at regular intervals.

A control valve installed downstream of the test article was used to maintain the back pressure at the test article outlet. At all times, the pressure at the test article outlet was maintained near one-half of the measured differential pressure across the test article at the tested flow rate.

The test program included AICD flow tests over a range of single-phase (oil only or water only) flow conditions. The tested fluid viscosities used a combination of the five different paraffinic base oils and tight temperature control (generally ±1°F) at a desired temperature set point based on the viscosity temperature dependence of each oil. The temperatures required to attain the desired oil viscosities were in the range of approximately 70°F to 110°F. At each test condition, the flow was recirculated through the flow facility and test article until steady-state pressure and temperature conditions were achieved. Then, the flow rate, pressure, and temperature data were recorded at two samples per second during steady-state flow conditions for a period of approximately two minutes. Five flow rates in the range of 0.5 gpm to 5 gpm were completed for each viscosity for each test article, and a flow versus pressure drop characteristic curve could be generated at each viscosity, for each AICD.

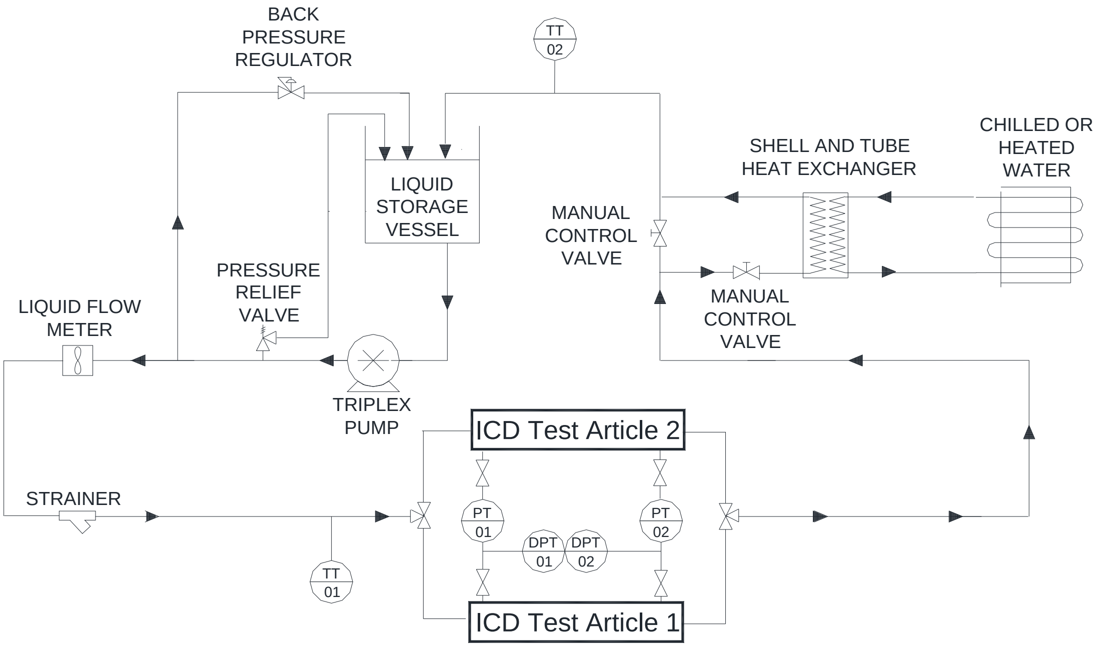

Figure 4. Schematic of Test Setup - The test setup provides liquid flow through one of two AICDs, oriented horizontally, at flow rates of up to approximately 5 gpm at an upstream pressure up to 1,400 psig.

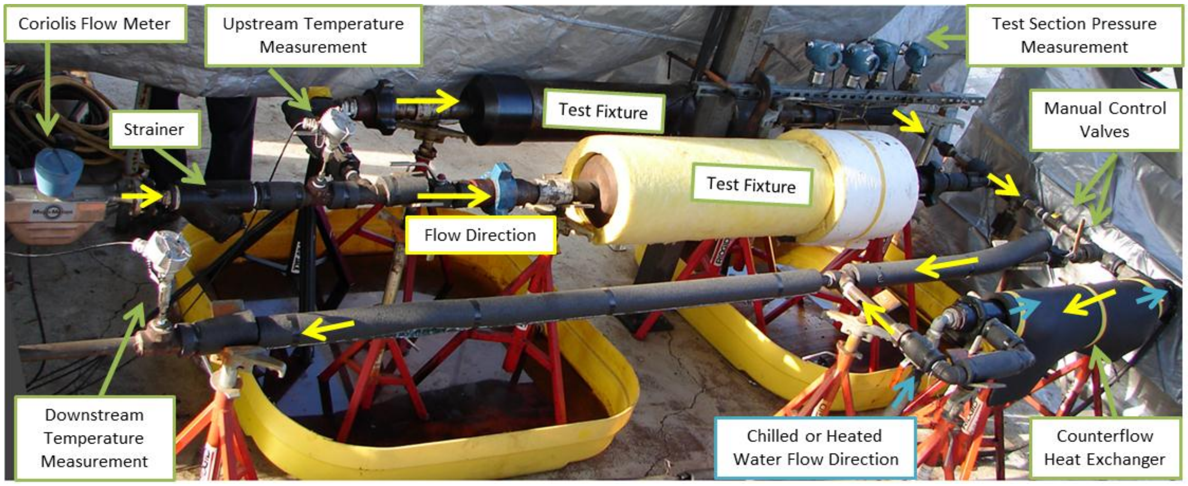

Figure 5. ICD Test Setup - The test setup was instrumented to measure the flow rate, the static pressure and temperature at the inlet and outlet of each ICD test article, and the differential pressure across each ICD test article (triplex pump and tank not shown in this picture).

RESULTS AND DISCUSSION

Flow characteristic curves were generated for both Range 3 and Range 4 single insert AICDs within the target viscosity range of each tool. Each tool was tested with fresh water at 1 cP and with oils with viscosities of 10, 45, 99, and 229 cP for the Range 3 AICD and 233, 449, 747, and 1002 cP for the Range 4 AICD. Steady state differential pressures were achieved at approximately 58, 218, 363, 508, and 653 psi and flow rate was recorded.

Tables 1 and 2 show data collected for the Range 3 and Range 4 AICD, respectively. For each fluid, the viscosity, density, and temperature are given. Flow rates varied for each fluid dependent on the target pressure differential.
Because of the geometries specific to AICD, it was expected for water to be restricted or have a lower flow rate compared to oil for a set pressure differential. The tools behaved as expected and water had a lower flow rate than all other fluids at any given pressure differential tested.

Figure 6 shows performance for a single insert Range 3 AICD. The flow rate of 10 cP oil was roughly double that of water at every pressure differential. The higher viscosity oils had approximately three times the flow rate of water for pressure differentials higher than 58 psi.

Figure 7 plots fluid viscosity vs. flow rate for set pressure differentials of 58 and 217 psi for the Range 3 AICD. Plotting the data in this manner allows a well operator to predict returns for the expected well pressure differential. It is clear that water, which has a viscosity of 1 cP, has the lowest flow rate compared to all oils tested. Another observation is that the AICD has an optimum viscosity at a given pressure differential. For example, for the data collected, 45 cP is the optimum viscosity for the Range 3 tool at 58 psi. The flow rate greatly increases as viscosity increases above 1 cP until it reaches some maximum point, then slowly declines while remaining well above the flow rate of water.

Figure 8 shows performance for a single insert Range 4 AICD. All oils had significantly greater flow than water at the same pressure. The AICD has a geometric advantage which enhances oil flow and restricts water flow. This phenomenon was more apparent at higher pressure differentials. At 58 psi the lightest oil, 233 cP, had the highest flow rate whereas at 653 psi the heaviest oil, 1002 cP, had the highest flow rate.

Figure 9 plots fluid viscosity vs. flow rate for set pressure differentials of 58 and 217 psi for the Range 4 AICD. Comparing this plot and Figure 8 it can again be observed that an optimum viscosity for the tool is dependent upon pressure differential. Water has a lower flow rate than oil at a given pressure differential and is restricted more greatly as pressure differential increases.

CONCLUSIONS

- The purpose of the AICD tool is to maximize oil production, restricting water producing zones and balancing flow across the completion. Several AICD tools function as a system in a well to accomplish this goal. This study focused on the behavior of an individual single insert tool to understand functionality. The results obtained can be used for completion design and flow prediction in a resevoir.
- Simply by flow path design and without the use of moving parts, both tools produce more oil of any viscosity tested than water. For most oils, this restricting effect increased as pressure differential increased.
- Each tool has an optimum viscosity which varies according to pressure differential. This information can be used to maximize AICD effects and should be considered when selecting the number of inserts for each tool and the number of tools that will be used in a completion.
- Single insert AICD tools were tested. This data can be scaled according to the number of desired inserts. For example, if the flow rate of an oil is 1.21 gpm at 57 psi for a single insert tool, then a tool with two inserts would be expected to have a flow rate of 2.42 gpm at 57 psi differential.
- The single insert tools were tested in a horizontal position, with the insert facing down. This was done to show that the tools are not gravity dependent. The Range 3 and Range 4 AICD tools function the same regardless of orientation.

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Table 1. Single Insert Range 3 AICD Performance Data

Fluid	Flow Rate (gpm)	Differential Pressure (psi)
1 cP Water 62 lb/ft³ 102 °F	0.53	58
	0.95	220
	1.18	364
	1.37	512
	1.52	655
10 cP Oil 53 lb/ft³ 84 °F	1.08	58
	1.80	215
	2.20	367
	2.50	510
	2.71	646
45 cP Oil 53 lb/ft³ 77 °F	1.52	58
	2.50	215
	3.15	365
	3.56	515
	3.93	665
99 cP Oil 54 lb/ft³ 97 °F	1.21	57
	2.43	214
	3.72	365
	4.41	506
	4.80	651
229 cP Oil 55 lb/ft³ 76 °F	1.00	58
	2.42	220
	3.38	362
	4.07	505
	4.65	659

Table 2. Single Insert Range 4 AICD Performance Data

Fluid	Flow Rate (gpm)	Differential Pressure (psi)
1 cP Water 62 lb/ft³ 109 °F	0.41	57
	0.76	213
	0.99	359
	1.17	514
	1.31	647
233 cP Oil 55 lb/ft³ 79 °F	1.07	57
	2.06	210
	2.59	359
	3.01	506
	3.32	650
449 cP Oil 56 lb/ft³ 94 °F	0.96	58
	2.10	218
	2.78	364
	3.28	505
	3.74	659
747 cP Oil 56 lb/ft³ 88 °F	0.77	58
	2.06	218
	2.78	365
	3.36	512
	3.76	627
1002 cP Oil 57 lb/ft³ 79 °F	0.61	58
	1.84	220
	2.69	361
	3.33	508
	3.87	646

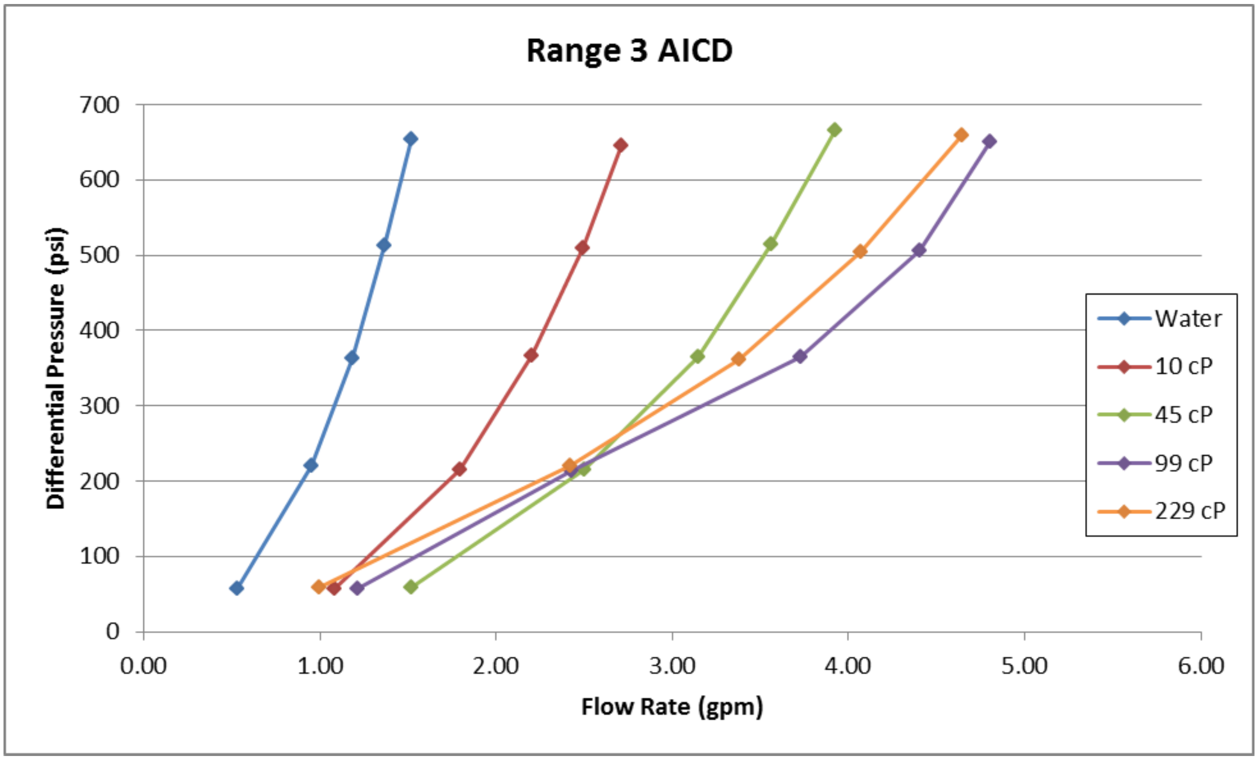

Figure 6. Single Insert Range 3 AICD Performance Curve

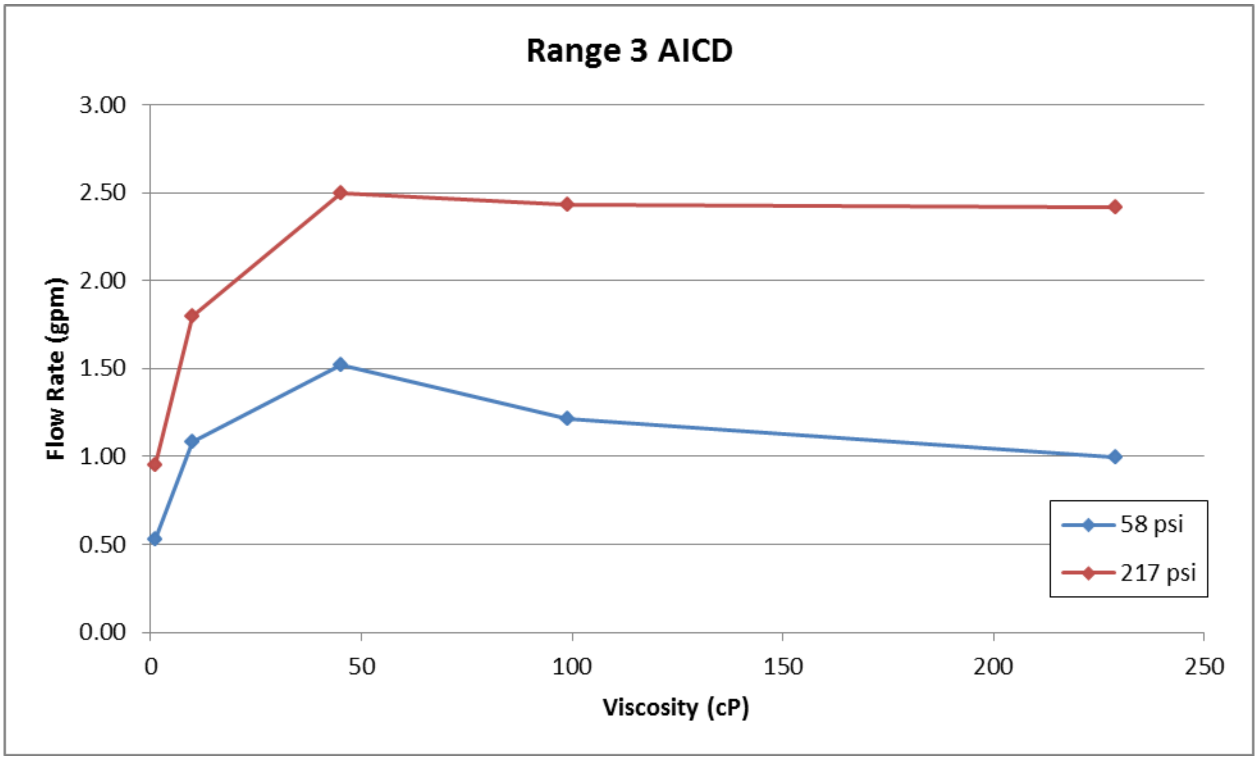

Figure 7. Single Insert Range 3 AICD flow rate vs. viscosity for set pressure differential

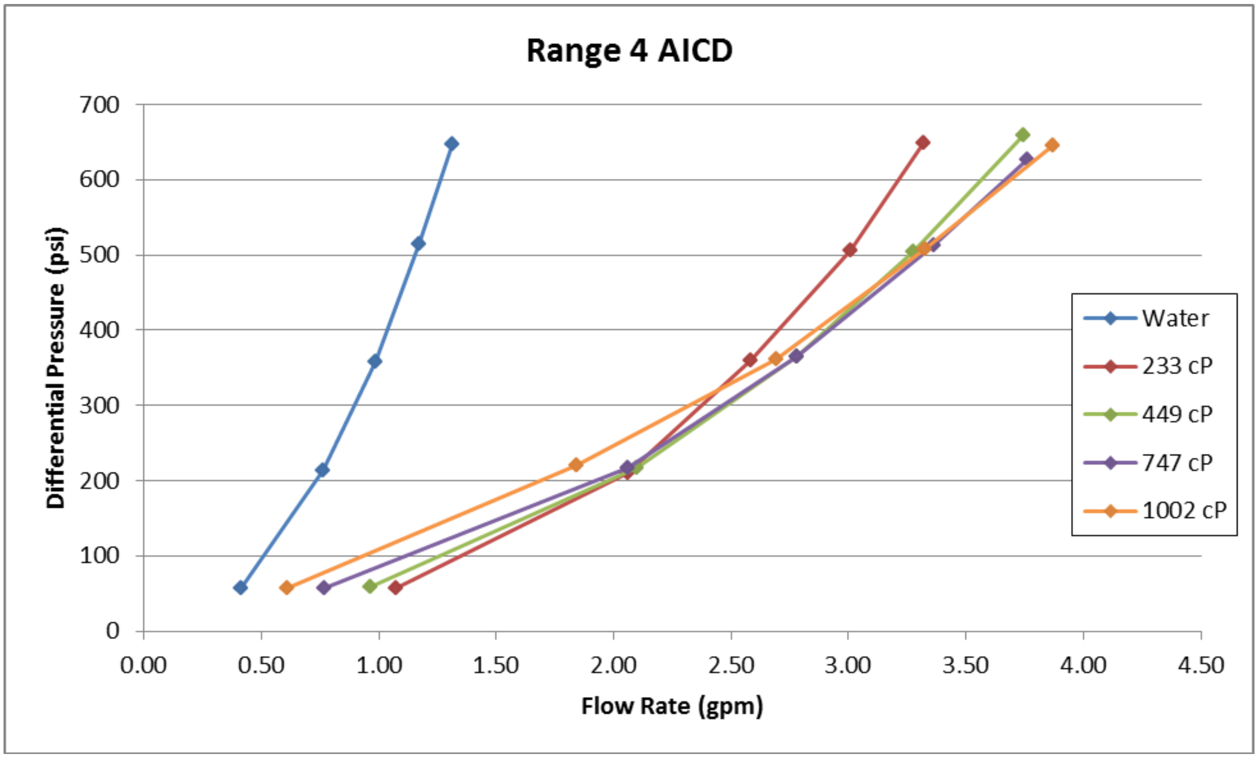

Figure 8. Single Insert Range 4 AICD Performance Curve

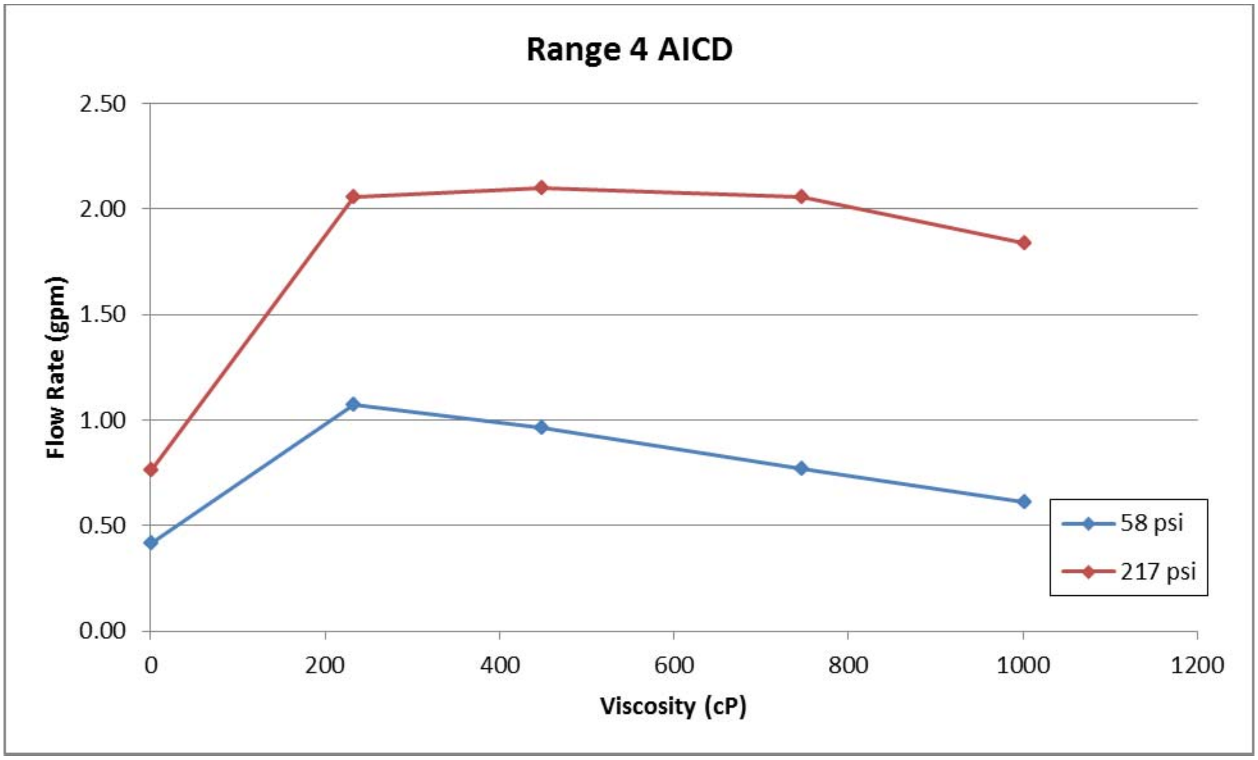

Figure 9. Single Insert Range 4 AICD flow rate vs. viscosity for set pressure differential