Automated High Pressure, High Temperature Foam Column Testing Apparatus
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Abstract
Continuous or batch treatment of low-pressure gas producing wells with foaming agents is a common and cost-effective method to sustain production from such wells. The foam additives convert gas and brines into foams lowering the bottomhole hydrostatic pressure and increasing liquids unloading from the well; thus, preventing wells from filling with water and “drowning”. The process can utilize existing formation gas or lift-gas injected into the well. Water to be unloaded can be from nearly drinking quality to supersaturated brine. Selection of a proper foaming agent for foam assisted well deliquification at downhole conditions becomes more complicated in deeper hot wells and with influx of various amounts of oil and condensate in well liquids. Common and standard bench foam testing methods are insufficient to assess foaming agents’ efficiency at extreme environments.

Answering the need for more realistic testing methodology of foaming agents an automated heated and pressurized foam testing column was constructed. The device is capable of injecting gas, brines, condensate and foaming agents at high pressure and bottomhole temperatures encountered in even deepest wells. Foaming agents’ effectiveness is measured at true well conditions. The paper describes design, testing procedures and compares results against older testing methods.

First laboratory obtained data on foams vertical movement at high pressure and high temperature wellbore conditions are described here. Measurements of foaming agents well deliquification abilities at temperatures above 100°C (212°F) are impossible to obtain with any other existing instrument. The results validate the original scientific idea behind constructing of device measuring foaming agents’ effectiveness at below critical velocity gas flows based on brine retention in the column. The foam column is becoming an indispensable tool for development of foaming agents to be used in challenging environments. This apparatus allowed moving the ultimate new product testing from the field back to the lab and avoiding costly mistakes.

Introduction
Foams have various applications in oil field. They are being used for cleaning, foam flooding or flow blocking. Two major uses of foams are in fracturing operations and in foam-assisted wells unloading. In older gas wells brines begin to accumulate in a wellbore when the gas velocity becomes insufficient to carry the fluids to the surface. Foaming agents added to formation fluids allow to convert them to lower density foams; thus, lowering the hydrostatic pressure in the wellbore and improving or restoring gas production from such “drowned” gas wells.

Foams for fracturing are high viscosity fluids capable to carry propants into gas or oil bearing formations. Foaming agents applied in deliquification must meet different requirements, they have several must have and must not:
- Produce low viscosity “wet” foams.
- Have to foam brines from low salinity to supersaturated ones containing mono- and divalent cations.
- Resist defoaming action of oil and condensate associated with gas production.
- Have to be compatible with production chemicals like scale and corrosion inhibitors.
- Resist decomposition at bottomhole high pressure and temperature.
- Cannot produce difficult to break emulsions and foams.
- Not to exceed maximum allowed oil carried into water phase.
- Cost effective to compete against other deliquification techniques.

Foams for different applications require different testing procedures. Foam agent manufacturers and end users have their own testing procedures, usually a modified ASTM method. They can be divided into two categories:
- Blender test – after high shear mixing static test measuring foam quality and half-life time (Figures 1 and 2).
- Column transportation test – measures foam growth and/or transportation liquids with time using fixed liquid volume and gas flow rate (Figures 3 and 4).
Test with 5% hydrocarbon phase, in 15 seconds foam separates from emulsion following with separation of emulsion from brine, second T½. Phase separations is difficult to observe.

Figure 1: Benchtop blender test near room temperature.

Figure 2: Inconclusive blender test results with oil and brine.

With more deeper and hotter wells reaching age qualifying for foam assisted deliquification requirements for foaming agents are more demanding. However, none of the published methods provide objective and quantitative results at true gas well environments.

**New Concept of Foam Testing Instrument**

Knowing deficiencies of testing foams at ambient conditions and being forced to extrapolate data into high temperatures we have created in the laboratory a testing environment that mimics dynamic conditions of gas production below critical flow
velocity ($V_c$). The device, Foam Transport Column, (Figures 5 and 6) is capable to quantitate foaming agents efficiency by measuring the volume of liquid retained in the well flowing below $V_c$.

Figure 5: Schematic drawing of Foam Transport Column. Pictures of installed electropolished and not polished pipes are on the right. Polishing was done to minimize friction.

Figure 6: Current view of the column. Two pumps and $\Delta p$ sensor are on the floor, heater and electronic boxes are on the table, gas valve and backpressure regulator are above the table level.
The instrument is a heated vertical pipe 5 ft high U shaped on the top with a return pipe terminated with back pressure regulator and a valve system allowing to collect samples of return liquids. The system is designed to reach up to 400°F (200°C) at 600 psi. The hardware is rated up to 5000 psi; however, such high pressure is not required. The system needs to be pressurized to keep all the liquid ingredients below boiling otherwise they would increase gas flow in uncontrolled way. Table 1 lists water boiling points with pressure and effective volume of 1 liter of gas at listed p/T conditions.

**Table 1**

<table>
<thead>
<tr>
<th>Pressure, psi</th>
<th>Temperature, °C</th>
<th>Temperature, °F</th>
<th>Volume 1 L gas std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>100</td>
<td>212</td>
<td>1.3</td>
</tr>
<tr>
<td>69</td>
<td>150</td>
<td>303</td>
<td>0.33</td>
</tr>
<tr>
<td>225</td>
<td>200</td>
<td>392</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Gas, brine, foamer and hydrocarbon are introduced at the bottom of the column. This artificial well cannot drown; all components are injected at pressures about 50 psi higher than the experiment pressure set with the backpressure regulator. All liquids entering the bottom must come out over the top. At a worst scenario no foam at all, the column would fill up to the top and then spill over to the return pipe. The FTC is fully automated, a computer controls liquids and gas flow, records temperature, absolute pressure and the differential pressure between the top and bottom that is proportional to volume of liquid in the column.

**Dynamic Measurements**

According to Coleman equation the expected Vc for this column is about 22 ft/sec (77 L/min N2) with no foamer. Minimum Vc is about three times smaller with surfactant in brine solutions. The value of measured ∆p is a function of three variables:

\[
\Delta p = f(\text{liquid rate, gas rate, foamer concentration})
\]  

(1)

There are four strings of data to visualize. Several experiments were done changing variables in equation 1 (Figure 7).

![Figure 7: 3D Differential pressure response to gas rate and foamer concentration change. Test results at constant brine rate 22 ml/min.](PSIPlot22mlStat.PDW)
The column $\Delta p$ responded very well to gas flow and foamer concentration changes. The best response was in foamer concentration 0 – 2000 ppm and gas flow rate 1 – 3 L/min. However, one important variable, the brine flow changes, has to be left out. To express all variables on one graph gas and liquid rates were combined as a ratio gas/liquid (Figure 8).

![Av. static dp](image)

Figure 8: 3D Differential pressure response to foamer concentration and ratio of gas flow to brine flow.

The largest $\Delta p$ response was observed for foaming agent concentration 0 – 2000 ppm and gas to liquid ratio 10 – 100 range. Several different liquid and gas flow rates were tried to find manually the flow rates combination producing the best ranges where $\Delta p$ values display the widest response to foamer concentration changes. This led to establishing standardized conditions for testing common foaming surfactants.

- Nitrogen flow below Vc 1 L/min standard conditions (0.4 L/min at 50 psi/90ºC, 194ºF) equivalent to gas velocity 6.6 ft/min.
- Brine flow 40 ml/min (90% foam quality if all liquid is converted to foam).
- Hydrocarbon flow 0 to 2 ml/min (5% of brine rate).
- Foaming agents used at two concentrations 500 ppm and 1500 ppm and more often at equal treatment price 0.1 ¢/L and 0.3 ¢/L.
- Brines received from the field or more often synthetic 0.6% TDS, 3.5% TDS and 20% TDS based on real produced water composition from several wells.

For the practical purpose of presenting data the $\Delta p$ value is converted to retained liquid level in the column (Equation 2)

$$h_{\text{liquid}} = \frac{\Delta p}{d_{\text{liquid}}}$$ (2)

Figure 9 depicts brine level changes in a standard 25 minutes test. Four stages of the test can be recognized:

**Filling Stage** The test begins with an empty column. Brine, foamer and gas are injected through bottom ports. If the brine/foamer combination produces stable foam, the foam is being transported out of the column and almost no fluid level is recorded. If the foam collapses before reaching the top, brine flows back down and accumulates on the bottom - the column is filling up. With higher brine level in the column the distance foam must go to be unloaded becomes shorter, so less efficient foamers producing shorter living foams eventually begin unloading. Since the components are always injected at pressure greater than the backflow pressure the column cannot drown. The worst results (i.e. distilled water or no foamer) show column 100% full with liquid spilling over the top.
Figure 9: Differential pressure converted to liquid level in a column. Two curves represent two 25 min long experiments with low and high concentration of a foaming agent.

- **Burst Through**: The filling stage lasts 5 to 15 minutes and usually ends with a small burst of liquids before the liquid level stabilizes itself.

- **Flow Equilibrates**: Volume of liquids unloaded and injected is the same; the liquid level in the column stabilizes and is directly related to foam viability the system can produce.

- **Dynamic and Static Data Collection**: ∆p values collected from 16th through 20th minute are averaged and reported as dynamic test. After 20 minutes the computer commands all flows stop and for last five minutes foams trapped in the column above liquids are allowed to collapse. Last two minutes of data are averaged and reported as static test. In reality these static data represent “frozen” dynamic flow. They provide less scattered numbers.

Assuming that no liquid is retained in the column corresponds to 100% deliquification and completely filled column is 0% deliquified one can calculate percent deliquification efficiency (Equation 3)

\[
\%_{\text{deliquified}} = 100 \times \frac{h_{\text{column}} - h_{\text{liquid}}}{h_{\text{column}}} = 100 \left(1 - \frac{\Delta p}{h_{\text{column}} - d_{\text{liquid}}} \right)
\]  

(3)

where: \( h_{\text{column}} = 177 \text{ inch} \), \( \Delta p \text{ [lb/inch}^2\text{]} \), \( d_{\text{liquid}} \text{ [lb/inch}^3\text{]} \)

A template was produced so that data from several standardized foam experiments can be imported and the software automatically produces one combined graph offering a clear picture of foamer efficiency (Figure 10).

Figure 10: Example of deliquification experiment in 3.5% TDS brine with foamer concentration 0, 0.1 and 0.3 ¢/L. Included dynamic and static results without and with 5% fuel oil in brine.
Figure 10 displays a graphic illustration of a foaming surfactant capability of unloading wells applied at different concentrations and hydrocarbon influence. Both, dynamic and static data are visible. The foam efficiently responded well to foaming agent concentration. It is clear this foam is sensitive to hydrocarbon contamination. The lines representing tests conducted with 5% oil in brine are 30% lower than those with no oil. Series of described above experiments on raw foaming agents and formulated mixtures produced a book of data useful in selecting or formulating new foaming agent for particular applications.

**What Can Go Wrong**

**Foamer overdose.** Excess of foaming surfactant in the solution produces viscous “shaving cream” type foam. Viscous foams have friction recorded as false brine retains.

![Figure 11: Foamer overdose illustration.](image)

Figure 11 depicts an example of extreme foamer overloading. Deliquification improves up to 3000 ppm of the foamer concentration and is showing decreased efficiency at 9000 ppm dosage. Another indicator of viscous foam in the column is when static data indicate higher deliquification efficiency than dynamic data. In normal situation after injection is stopped and foam is allowed to collapse, added weight of collapsed foam indicate higher level of liquids in the column than dynamic data and consequently lower deliquification efficiency.

**Corrosion and scale.** Hot brines containing divalent cations are corrosive to 316 stainless steel. After initial operation period of FTC some SS316 parts had to be replaced with more corrosion resistant alloys. Scale can form in hot brines containing carbonates sulfates phosphates and divalent cations. It is a problem for field supplied brines and unexpectedly persistent calcium phosphate scale was found forming on porous surface of gas sparger (Figure 12). The phosphate source was traced to small amounts of phosphates in scale inhibitors and some corrosion inhibitors.

![Figure 12: Titanium gas sparger covered with scale (half scale was scraped off before the picture was taken).](image)
Conclusions
Foam Transport Column was designed and constructed to fulfill a need for more realistic testing conditions of well deliquification foaming agents. More laboratory results and correlation between FTC data and field production are being published. The FTC device is:

1. Capable of testing foaming surfactants performance at gas wells downhole conditions
2. Delivers quantitative and objective results
3. Unique product development tool eliminating potential costly mistakes. Gives a highest confidence while moving a foaming agent from a laboratory to the field.
4. Testing foaming surfactants at well conditions assess their genuine foaming potential; hence, assists end users in selection of best foaming agents for particular downhole conditions.
5. Safety improvement. FTC eliminates human exposure to hot fluids.

Acknowledgements
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References
2. ASTM methods D-3519, D-892, D-3601 are frequently modified.
5. For more testing results and brines compositions see M. Pakulski “Testing Gas Well Deliquification Chemicals at Real Downhole Conditions”, SPE 121564 presented at the SPE International Symposium on Oilfield Chemistry, The Woodlands, Texas, 20-22 April, 2009. Correlation between FTC laboratory results and field production data will be reported elsewhere.

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