Field Testing of New Technologies for Lifting Liquids from Gas Wells

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Abstract

When initially completed, many natural gas wells are capable of lifting liquids to the surface. But, with depletion of the reservoir pressure, there comes a time when liquids can no longer be lifted to the surface and they begin to accumulate in the bottom of the well, dramatically inhibiting or stopping gas production. The cause of diminished liquid-lifting ability is the decline of liquid droplet production at gas flow rates below the Turner-Hubbard-Dukler critical velocity.

In a previous project supported by SWC, devices for stimulating droplet production were studied with bench-top and flow-loop testing. Listed below are the two proposed tasks for this stage of the project.

Task 1: Field testing of new technologies. Using results of the previous SWC project, proceed to field testing of the most promising technologies. Choose a suitable business partner for these tests. Continue tests in the flow loop as needed to support field tests.

Task 2: Integrated modeling of gas well production. Continue to develop numerical models that combine the complexities of two-phase flow in the wells and the adjacent reservoir with the droplet-stimulation technologies. Use these models to design and interpret field tests.

Accomplishments for each of these tasks are summarized below.

Task 1: Field testing of new technologies. Vibrational, rotational, and two-fluid devices were tested in the previous project. In flow loop tests, the rotational device failed to provide droplets for transport. The two-fluid devices were more promising, but most of the droplets impinged on the walls of the 2.5-inch-ID tubing. These devices might be more applicable for application in large diameter tubing or casing. The vibrational devices provided very small droplets that were easily transported in the flow loop. We chose to focus efforts on developing vibrational devices for field testing.

Two prototypes were assembled and tested in the flow loop. Each prototype consisted of a 2-MHz ultrasonic transducer inside of a cylindrical PVC housing. The OD of the housing is 2.13 inches. This is the smallest diameter that could accommodate the transducer. This device was suitable for testing in the flow loop but was not robust enough for field testing. As anticipated, difficulties with protecting the electronics from water were encountered. Two approaches were designed for dealing with water. One was tested in the flow loop.

The prototypes also lacked a water sensor for preventing "burning" of the piezo-electric disk of the transducer. Suitable sensor technology was identified but not tested.

In the prototypes, a four-wire cable was used to provide the 48 volt power to the transducers. For field testing, such a cable would not be sufficient.

Task 2: Integrated modeling of gas well production. We continued simulation of the reservoir-well system with Eclipse 100 models. The models used in these simulations consisted of a single well and adjacent productive formations. The performance of the well was included in a very approximate manner – improving the representation of the well in such simulations is a challenge. Models for wells with and without hydraulic fractures were used. A wide range of reservoir permeabilities and relative permeabilities were studied. The results of these simulations show that incomplete removal of water from wells can diminish ultimate gas recovery by as much as 20%, depending on the properties of the reservoir. To avoid these losses of recovery, contact of the producing formation with liquid water in the well must be minimized.

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Description of Approaches

Task I: Field testing of new technologies. In the first phase of this project sponsored by SWC, we studied production of droplets by three approaches: vibrational, rotational, and two-fluid devices (Christiansen, 2003). All three approaches produced sufficiently small droplets in bench-top tests. The bench-top tests also demonstrated well-documented features of these three approaches: rotational and two-fluid devices impart a significant velocity to the produced droplets, while the vibrational devices produce low velocity droplets. The importance of these features was very apparent during tests in the flow loop. Droplets from the rotational device impinged almost immediately on the walls of the tubing. The two-fluid devices were more promising, yet about 70% of the droplets impinged on the walls. Most if not all of the droplets produced by the vibrational devices were lifted to the top of the 40-foot flow loop. As a result, we eliminated rotational devices from further consideration. We speculated that two-fluid devices might find application for droplet generation in larger diameter tubing or casing. And we chose to focus efforts for the second phase of the project on vibrational devices.

In this second phase of the SWC project, we developed two prototypes of vibrational devices for converting bulk liquid into very small droplets in a gas well. Both of these prototypes were designed to use a commercially available ultrasonic transducer that is manufactured by TDK. Figure 1 shows the mist production rate for the TDK transducer as a function of temperature.

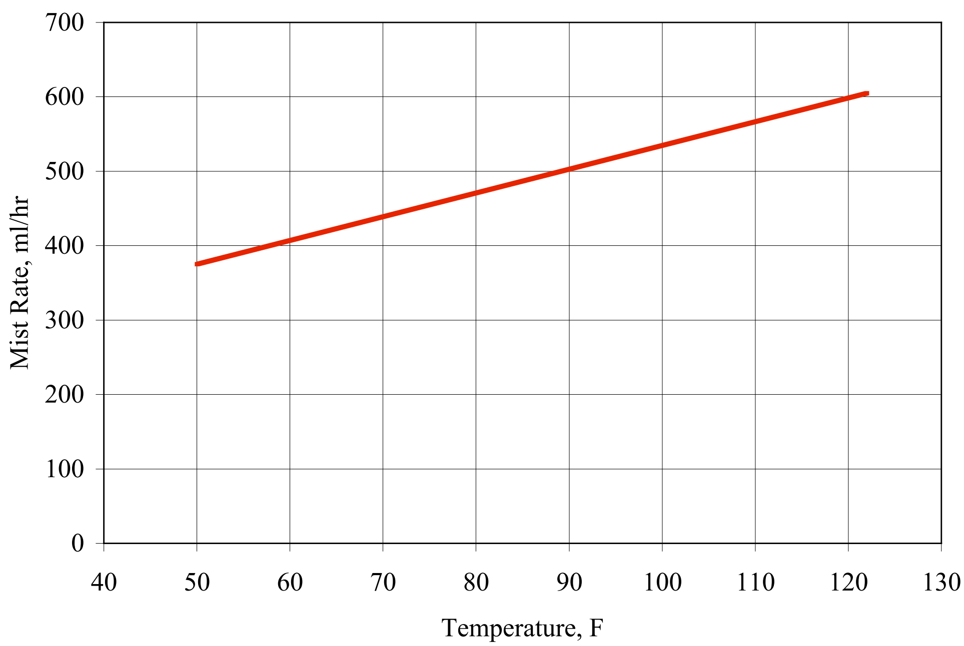

Figure 1. Mist production rate for TDK transducer.

TDK is the only manufacturer of transducers that provides technical description of their product. The upper limit for operation of the TDK transducers is 140˚F, so the application of these transducers is limited to wells with bottom-hole temperatures less than 140˚F. As there are many gas wells in this category, this limitation is not a near-term issue. The rate of mist production for the TDK transducer is about 600 ml/hr at 120˚F. This corresponds to about 0.1 bbl of water per day. Clearly, more than one transducer would be needed for most gas wells. But for demonstration of the concept of mist production with a vibrational device, the TDK transducer is the best choice. Mist production rates for other readily available devices are about 50% of the TDK rates.

Sketches of the two prototypes are shown in Figure 2. These prototypes consist of 2" clear PVC pipe with end-caps, supports for the piezo-electric (PZ) disk, chambers for the TDK electronics, and aluminum heat sinks, and windows to allow liquid to accumulate above the PZ disk assembly.

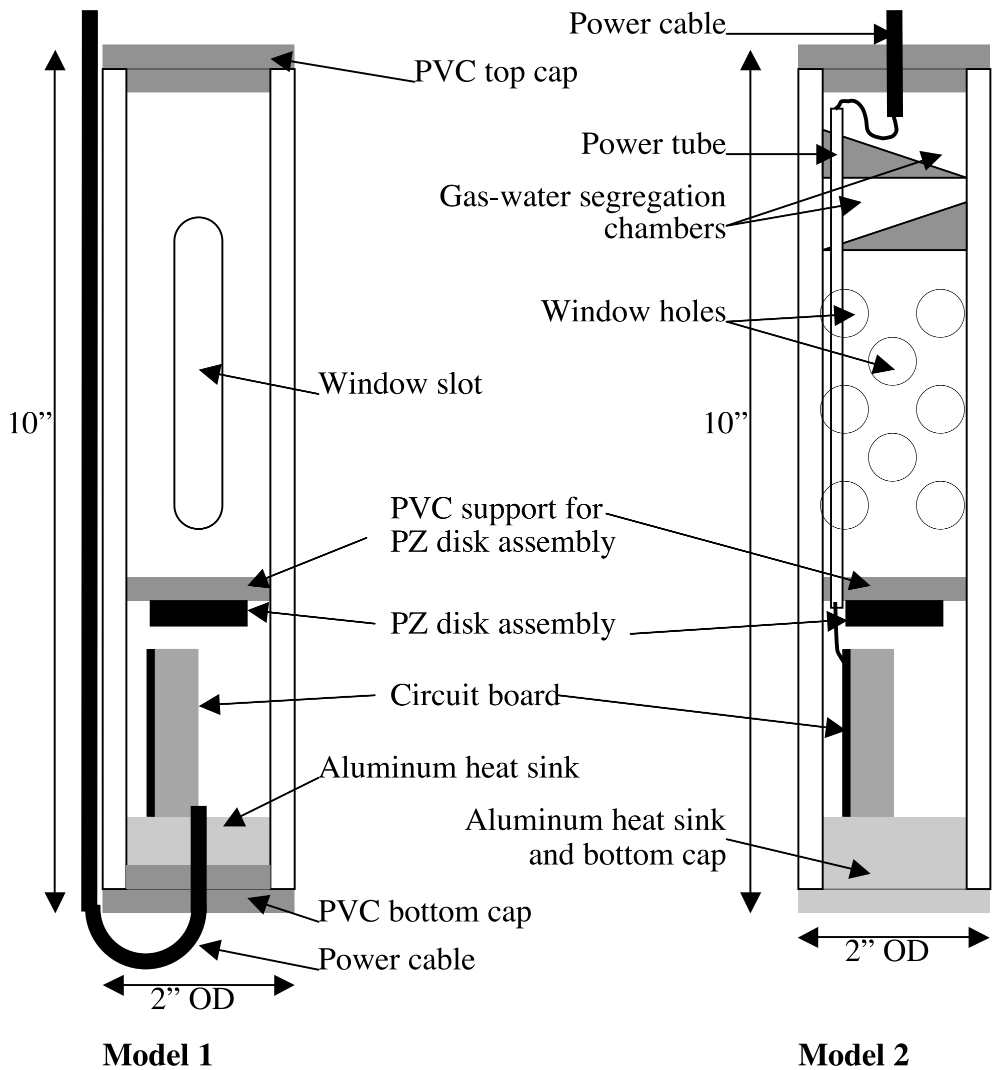

Figure 2. Two prototypes for vibrational devices.

The two prototypes share many features, but differ in some important aspects. In Model 1, the power cable passes by the side of the device and enters through the bottom cap. During vigorous flow testing of this model, water entered the electronics chamber and caused it to fail.

The water probably entered through the seals on the PZ disk assembly during pressure surges. This problem was anticipated because the PZ disk assembly was not designed to support large pressure differences. To eliminate this problem in Model 2, the power cable enters through the top cap, and the power wires travel down the power tube to the electronics chamber. Gas can also pass through the power tube, which allows pressure equilibration between the gas outside of the electronics chamber and the gas inside the chamber. Thus, the pressure is balanced across the PZ disk. The power tube allows equilibration of pressure, but it could also allow water entry to the electronics chamber. To prevent that, two chambers were provided for water to segregate from gas.

Dispersion of heat from the power transistor on the TDK electronics was another concern. In Model 1, the circuit board was attached to an aluminum heat sink that rested against the bottom cap, also made of aluminum; however, this approach did not effectively reject heat to the outside flow. So in Model 2, the function of the heat sink was combined in one piece with the bottom cap, greatly increasing the heat rejection capacity. This approach also simplified assembly of the prototype.

Two different designs of windows for collecting liquid and expelling mist were tested in the two models. In Model 1, two long slots were cut into opposite sides of the 2" PVC pipe. In Model 2, an array of circular holes was cut.

According to TDK specifications, the PZ disk should be submerged in about 40 mm of water for proper operation. If water level falls too low, then the PZ disk overheats and fails. To prevent this fatal condition, a water-level sensor is needed. Neither of the prototypes has a water-level sensor because I do not know how to integrate a sensor with the TDK transducer. The absence of a water-level sensor is an inconvenience for testing of these prototypes, but testing could proceed as long as great care is exercised to maintain sufficient water level above the PZ disks. Water-level sensors are absolutely necessary for field testing. Inclusion of those sensors in a field-suitable device will have to wait for a future project.

I would very much have liked to build prototypes with smaller outside diameters. Indeed, some preliminary designs were sketched. But those designs required custom electronic circuit boards and were eliminated from further consideration. Models 1 and 2 have about the smallest possible diameters for using the TDK transducer. Indeed, I had to remove the heat sink provided by TDK and shave almost 1/16" off the width of the TDK circuit board to allow it to fit in the 2" pipe. With more resources to develop custom electronics, prototypes with diameters of 1.0 to 1.4 inches are very possible. But as is often the case with research such as this that explores the fringes of what is possible, compromises are needed to make progress.

After constructing the models, they were first tested on the bench and then in the flow loop. The lay-out of the flow loop is shown in Figure 3. The prototypes were suspended by the power cable, 2 to 3 feet above the bottom of the flow loop. Prior to a test, the horizontal pipe at the bottom of the flow loop was filled partially with water. During a test, air flowing through the horizontal section blew water onto the prototypes. The rate of collection of water above the PZ disk inside the prototypes was noted. Flow rate of air was varied to assess transport of droplets. In all tests, transport of droplets was detected by scattering of light from a He-Ne laser beam and by collection of water in the gas-liquid cyclone separator.

Tests in the flow loop were done in a vertical 4-inch-ID PVC tube. This larger diameter was needed to accommodate the OD of the prototypes. The prototypes would fit inside a 2.5-inch-ID tube, but the close fit would not allow for any significant gas flow rate. Furthermore, if the misting approach actually proves viable, it would make sense to pull tubing and produce through casing whenever possible. That would minimize pressure drop and increase productivity of wells.

As noted earlier in this report, the goal of Task I was to test the devices in a field setting. Although I made a lot of progress in that direction, the prototypes fall short of what is needed to survive a field test. As noted above, a sensor is needed to detect the level of water above the PZ disks, turning electric power on or off in response to liquid level. That technology was not included with the TDK transducers. In May 2003, I found a person who could have provided the expertise to do those and other modifications. I intended to pursue that option during Summer 2003, but project funding was not extended soon enough to pursue that. By the time funding was extended in August, my time was very limited by the onset of duties for the Fall 2003 semester.

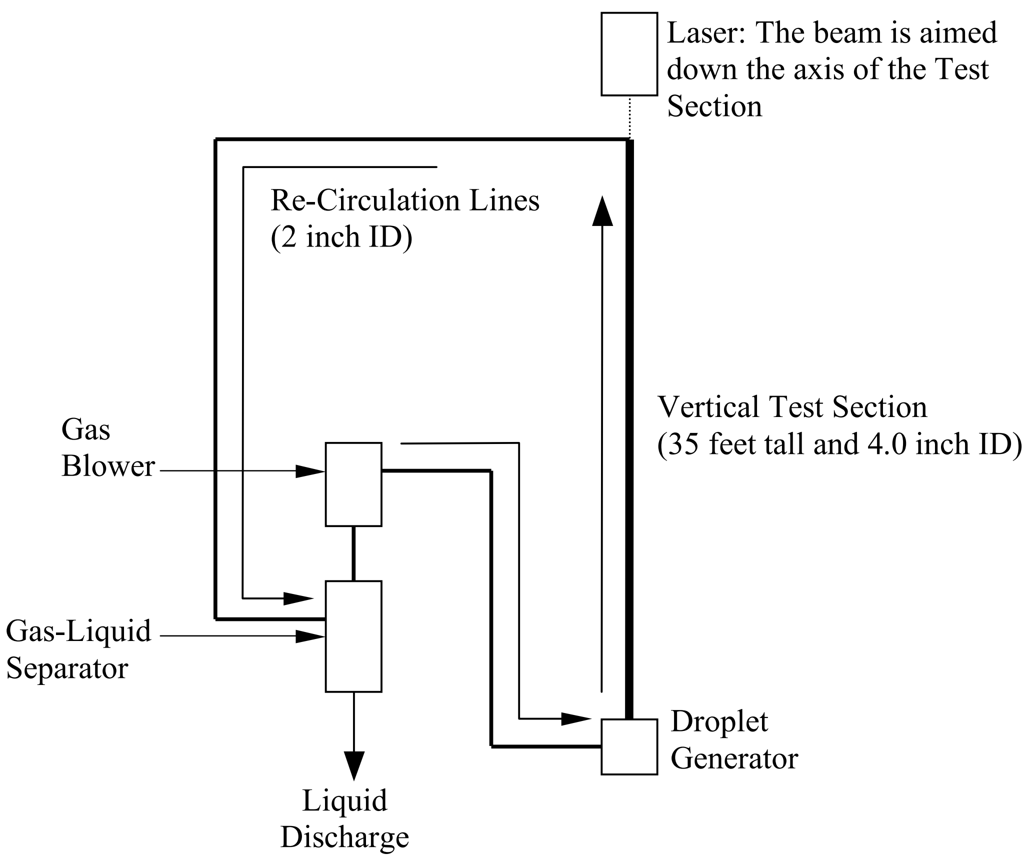

Figure 3. Schematic of Flow Loop.

Task II: Integrated modeling of gas well production. In this task, we continued efforts to model the combined system that consists of the reservoir and the well. We hoped that this effort would increase our ability to plan and interpret field tests of lifting technology, as well as our understanding of the benefits of effective liquid lifting. Although we did not complete an integrated model, we did investigate separately the reservoir and well-bore issues with modeling. We developed several models of gas reservoirs using Eclipse 100. Again, these single-well models were not integrated models – they are just reservoir models. However, we adjusted the operation of the well to reflect problems that occur in gas reservoirs. Specifically, we converted the well from a gas producer to a water injector at regular time interval to simulate cessation of gas production and the consequent imbibition of water that should have accumulated in the well-bore. The amount of injected water is small – less than 10 barrels. Such small amounts of water could accumulate in the production tubing during normal gas production; when production ceases, it would fall to the bottom of the well where it can be imbibed by the producing formation.

I also wrote well-bore models in Excel Visual Basic using the Gray model and the Duns and Ros model as described by Brill and Mukherjee(1999). These models were used mostly to investigate operating conditions in the flow loop.

Results and Discussion

Task I: Field testing of new technologies. This section begins with a brief discussion of the context of the problem of liquid lifting, continues with results of our research, and ends with discussion of feasible approaches for application of the results.

The root of the liquid-lifting problem in gas wells is droplet size. At high gas flow rates, liquids break into droplets of sufficiently small size for lifting by the gas. With decreasing gas flow rate, both the droplet creating capacity and the droplet lifting capacity decrease. This idea was succinctly represented by Turner, Hubbard, and Dukler (1969) in their expression for critical gas velocity v_c – the minimum velocity for dispersing and lifting liquid as droplets:

$$v_c = 0.567\left[\frac{(\rho_l - \rho_g)\sigma_{gl}}{\rho_g^{\ 2}}\right]^{1/4} \qquad 1$$

Here, the critical velocity has units of ft/sec, the liquid density ρ_l and the gas density ρ_g have units of g/cm^3, the gas-liquid interfacial tension σ_{lg} has units of dyne/cm. If the velocity of gas declines below v_c, then liquid accumulation begins. For a natural gas-water system at 311 K and 689 kPa (100˚F and 100 psia), the critical velocity is about 6.7 m/sec (22 ft/sec).

In our previous research, we sought ways to stimulate production of droplets that can be lifted by velocities less than the critical velocity of Eq. 1. At critical velocities that are common to many of the gas wells in the Rocky Mountains, the droplets can be as large as 3 to 8 mm in diameter. Our previous studies showed that much smaller droplets could be produced by vibrational means. A correlation of droplet diameter and vibrational frequency is shown in Figure 4. According to Lang(1962), the size of droplets produced by vibration can be estimated with the following expression:

$$d = 0.34\left(\frac{8\pi\sigma_{gl}}{\rho_l f^2}\right)^{1/3} \qquad 2$$

In this expression, d is the droplet diameter(m or cm), σ_{gl} is the gas-liquid interfacial tension(mN/m or dyne/cm), ρ_l is the density of the liquid(kg/ cm^3 or g/cm^3), and f is the vibrational frequency (Hz or cycles per second). Tests performed in our previous project show that the Lang correlation can be extended to a very wide range of frequencies. One of the images from the droplet formation tests of our previous SWC project is shown in Figure 5.

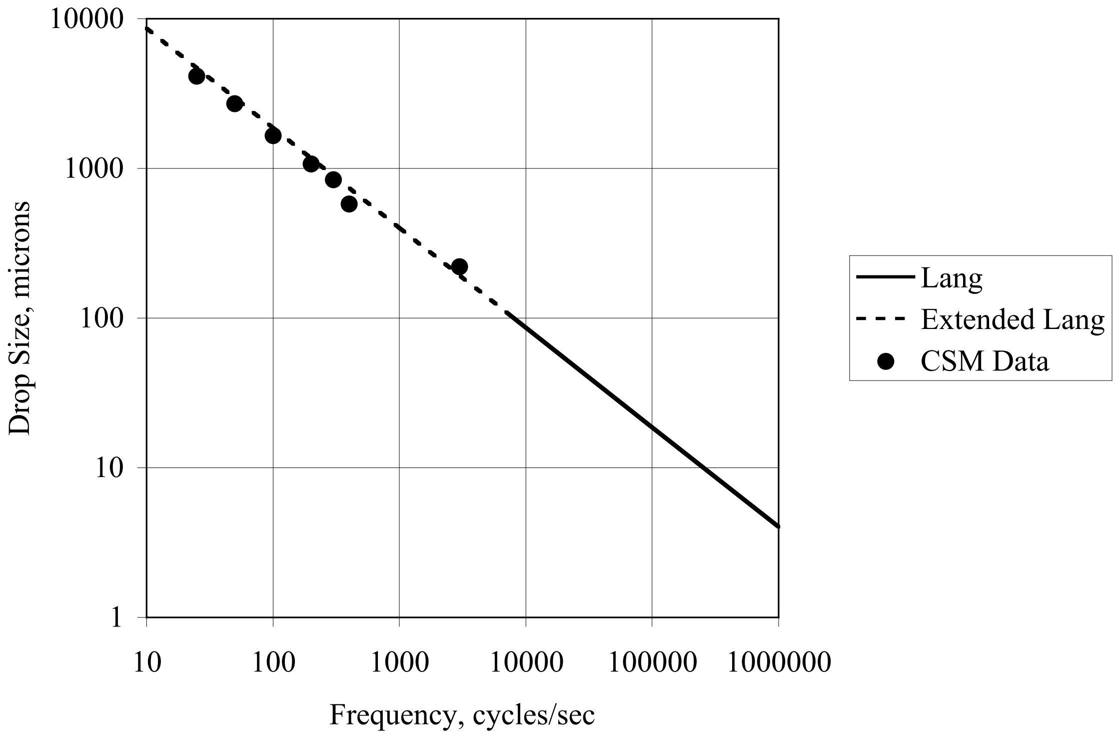

Figure 4. Extrapolating Lang's correlation to low frequencies quantitatively predicts our bench-top measurements.

Figure 5. Droplet formation at 200 hz.

As noted in previous sections of this report, the focus of Task I was to develop a device for field testing the vibrational approach for making very small droplets. Two prototypes were developed and tested in our flow loop. The objectives of these tests were to probe weaknesses in the designs of the prototypes and to assess the capacity for transporting the mist produced by the probes.

In tests with Model 1, gas flow rate was varied from about 5 MCF/day up to about 90 MCF/day. At rates up to about 60 MCF/day, the mist was carried up the 40 feet of the visible flow section and down the 40 feet of return tubing. At the highest flow rates, droplets impinged on the wall of the tubing. Furthermore, tests at the highest flow rates terminated prematurely because water partly filled the electronics chamber, disabling the transducer. At the highest flow rate, the prototype was subjected to pretty severe jostling as it was pelted with slugs of water.

The design of Model 2 responded to some of the weaknesses of Model 1. First, the aluminum heat sink was modified to take on the additional role as the bottom cap of the electronics chamber. This modification provides for more rapid transfer of heat to the flowing stream of gas and water around the prototype. Second, the power tube was added to provide a route for power connection through the top of the prototype and to provide a path for equalizing the pressure between the electronics chamber and the surround environment. Pressure equalization was needed because the PZ disk assembly is incapable of supporting more than a few tenths of a psi of pressure difference. Segregation chambers were added at the top of Model 2 to minimize opportunity for water entry into the electronics chamber through the power tube.

Tests with Model 2 have produced two interesting results. First, there was no entry of water into the electronics chamber through the power tube. Second, droplets were successfully transported even at the highest flow rate. The difference in droplet transport for tests with Models 1 and 2 is not understood. A bench-top test of Model 2 is shown in Figure 6. The mist can be seen flowing from the ports on the side of the model.

Figure 6. Bench-top test of Down-hole Device Model 2.

Both prototypes experienced a number of minor failures during testing that often consumed considerable time and patience to repair. As noted previously, there is no water-level sensor in the prototypes. Hence, one must be careful during operation to maintain sufficient water in the chamber above the PZ disk to prevent its self-destruction. The disk will self-destruct in a few seconds if there is not adequate water in the chamber. It is easy to lose track of this during testing process.

Neither of these prototypes is suitable for field testing. First, a level sensor is needed to prevent self-destruction of the transducers. Second, additional study is needed on the cable for providing power and support for the device. Third, a more robust mechanical design would be needed. The bottom cap is attached to the device with silicone sealant, which is sufficient for flow loop tests but not for field tests.

Task II: Integrated modeling of gas well production. For this task, I hoped to combine a model of reservoir behavior with a model of well-bore behavior. While this may be possible, I was not able to accomplish it within the time frame of this project. I was able, however, to complete some analysis of the two separate problems.

First, we wrote Eclipse 100 models to simulate the effects of water accumulation on gas production. One of the Eclipse 100 models is a radial model with horizontal permeability of 10 md, and vertical permeability of 1 md. The model is 60 feet thick. Cumulative production and production rate are shown in Figures 7 and 8 for a period of about 2200 days. Figure 7 shows that the cumulative production for periodic shut-in with re-injection of a small amount of water is about 20% less than that for continuous production of gas. Figure 8 shows the corresponding variations in gas production rate. After injecting water during the shut-in period, the gas production rate slowly rises toward the rate that is found for the continuous production model. Clearly, water that is not removed from the well has a significant detrimental effect on ultimate gas recovery.

The effect of changes in relative permeabilities and capillary pressure were on gas production were also explored with the radial Eclipse models. Relative permeabilities of the form of modified Brooks-Corey expressions were used in these models:

$$k_{rw} = k_{rw,\max}\left[\frac{S_w - S_{wr}}{1 - S_{gc} - S_{wr}}\right]^{nw}$$

$$k_{rg} = k_{rg,\max}\left[\frac{S_g - S_{gc}}{1 - S_{gc} - S_{wr}}\right]^{ng}$$

Specifically, we tested the effects of the exponents *nw* and *ng*. Increasing one of these exponents decreases the relative permeability of the associated phase. The results of these tests are shown in Figure 9 for intermittent injection of water as described in the previous paragraph. With *nw* and *ng* both equal to two, the effect of intermittent water injection on cumulative gas production is small. The effect on cumulative gas production increases as the exponents become larger. Values of *nw* are frequently between 3 and 5. (See Chapter 1 of Christiansen, 2001.) Generally, it is expected that exponents for the gas phase will be smaller than those of the water phase, because the water is considered the wetting phase. Relative permeabilities for very low permeability formations are rarely measured. Such measurements would be useful for evaluating the effect of water on cumulative gas production for the large gas reserves in the Rocky Mountains.

Changes in the threshold pressure of the capillary pressure relationship in the Eclipse model did not lead to significant changes in daily and cumulative gas production. This is surprising because I expect that the physical dimensions of the water saturated zone near the gas producing well to increase with increasing threshold pressure. This is a topic that deserves further study.

We also tested the effects of water on cumulative production from a “Cartesian” Eclipse model. In this model, a hydraulic fracture was simulated with a high permeability zone. Water was injected both intermittently and continuously into the portions of the fracture and the neighboring lower permeability reservoir. Results of these simulations were similar to those observed for the radial model.

These results suggest that a more careful evaluation of the effects of water on gas production is needed.

Second, I wrote Excel Visual Basic modules for well-bore simulation with the Gray model and the Duns and Ros model for two-phase vertical flow. (These and other two-phase flow models are described in Brill and Mukherjee.) I tested these models against performance in our flow loop. These models provided a lot of insight for interpretation of well-bore behavior, but there is much room for improvement. For example, many engineers in the industry maintain that a modified Hagedorn-Brown model is best for representing well-bore behavior. Other engineers favor mechanistic models. I used the Gray model primarily because it was very easy to write and it is widely used for simulation of wells with high ratios of gas to liquid production volumes. I chose the Duns-Ros model because of its foundation in laboratory data and because it provides a fairly comprehensive capability for well-bore modeling – it can represent bubble flow, slug flow, the transition from slug flow to annular mist flow, and annular mist flow regimes. These Excel Visual Basic modules are particularly useful for studies with the flow loop, but for actual well studies commercially available software is more useful. Such software incorporates heat-transfer effects, reservoir performance, complex well and surface designs along with the two-phase flow models.

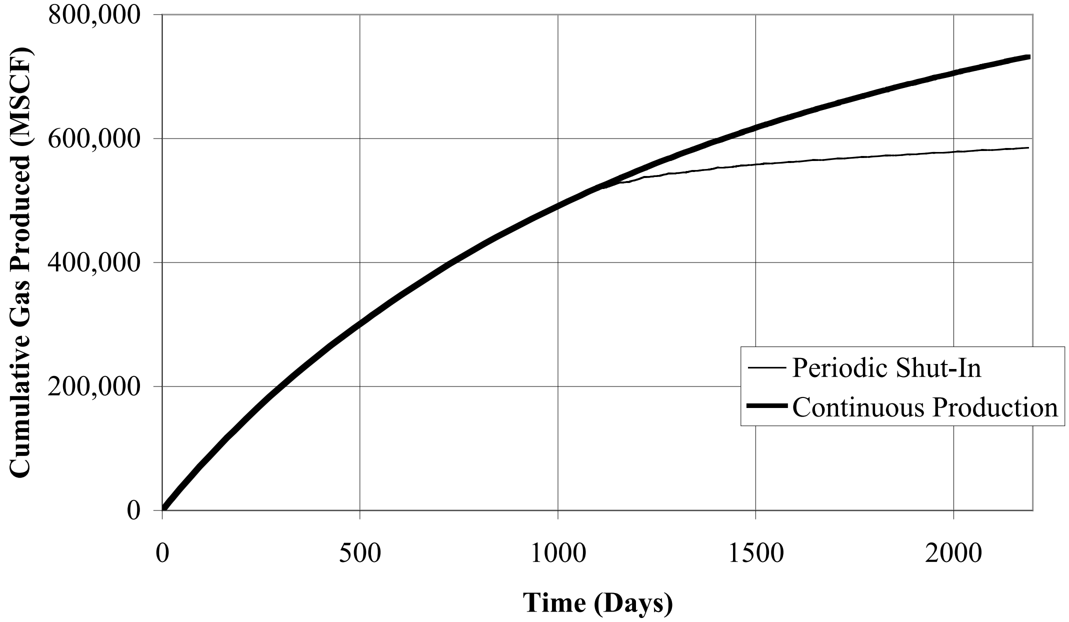

Figure 7. Cumulative production history for continuous production and for production with intermittent shut-in with water injection.

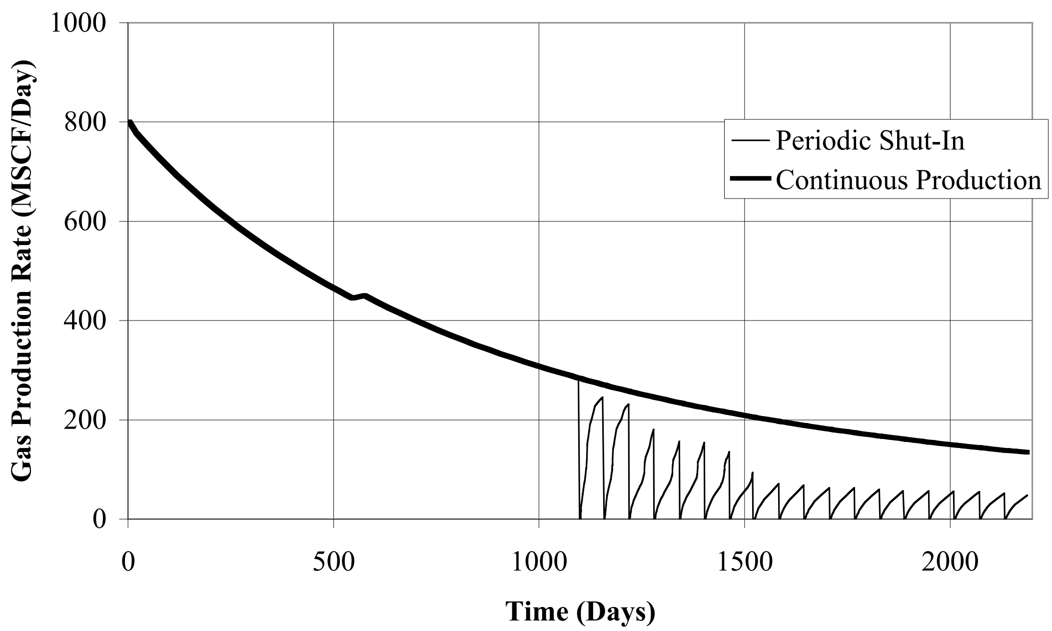

Figure 8. Production-rate history for continuous production and for production with intermittent shut-in with water injection.

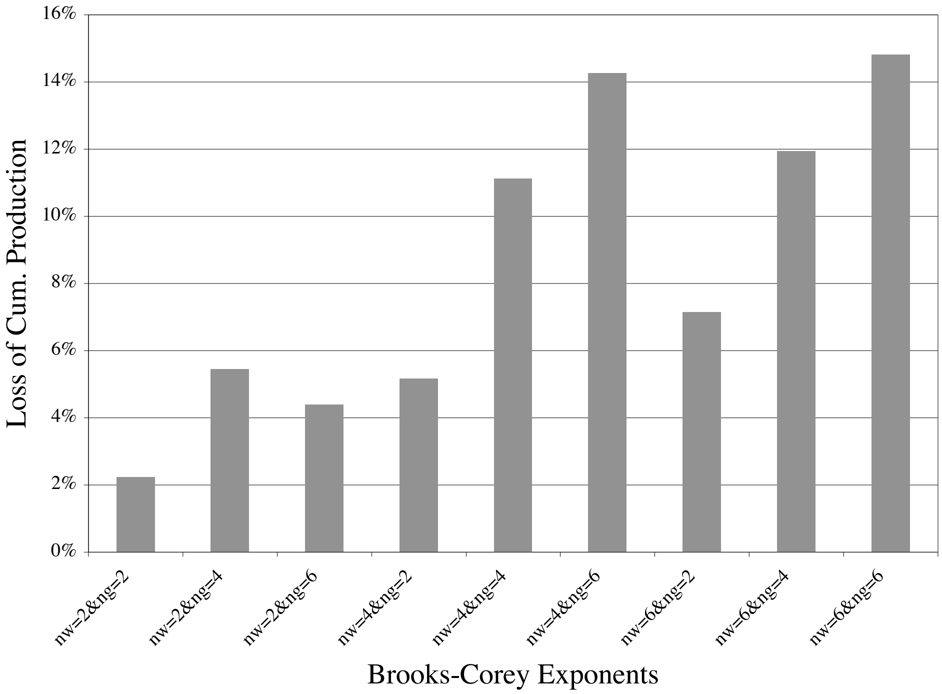

Figure 9. Loss of cumulative production after ten years with intermittent injection of water.

Conclusions

1. Droplets in gas wells at the critical gas velocity have maximum equivalent diameters of 3 to 8 mm according to analysis that is consistent with the model proposed by Turner *et al.*(1969).
2. Bench-top tests and analysis show that production of small droplets is possible with vibrational, rotational, and two-fluid devices. The Lang(1962) correlation quantitatively predicts the average size of droplets produced by vibrational means for frequencies from 20 Hz to 1 MHz.
3. Flow loop tests with 1.6 MHz ultrasonic transducers showed that 3-micron droplets can be transported a long vertical distance. Literature on separating liquid droplets from gas streams support this observation. We expect that droplets up to 30-microns can be transported to the surface. Flow loop tests with rotational devices failed completely. Flow loop tests with two-fluid devices were moderately successful.
4. The estimated energy costs of droplet production are low per stage: 3 to 30 cents/bbl for production of 30-micron droplets. If the droplets are less than 30 microns in diameter, just one stage may be sufficient. For larger droplets, multiple stages will be needed in a typical gas well.
5. Feasible approaches for application of vibrational droplet generators have been developed.
6. Simulation results show that production from gas reservoirs can be significantly diminished by incomplete removal of water from the wells.

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