CAVITATING AND STRUCTURED JETS FOR MECHANICAL BITS TO INCREASE DRILLING RATE: PART II, EXPERIMENTAL RESULTS

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Analyses of self-excited, resonating jets have been corroborated by laboratory experiments. These structured jets achieved cavitation at greater ambient pressures and showed enhanced erosivity in comparison to the nonstructured jets from conventional drill bit nozzles.

INTRODUCTION

In a companion paper [1] the theory and concepts for self-excited, resonating nozzle systems were described. These analyses showed that the structured flow issuing from such nozzles should afford several advantages relative to the conventional nozzles now used in deep-hole drill bits, namely: greater ability to erode or otherwise weaken the rock, and an improved mechanism for removing chips from the hole bottom. The experiments described in this paper have demonstrated the feasibility of creating such passively structured jets, and their potential for increasing drilling rates has therefore been confirmed.

EXPERIMENTAL FACILITIES

Two facilities were developed to study the characteristics of self-resonating jets. An air facility allowed examinations of jet performance with the capability of rapid and economical changes in a design iteration that were not so readily made

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in the high-pressure water jet facility. Although the existing air facility was operated at Reynolds numbers too low to allow complete scaling to the water results, valuable insights which guided and minimized the more tedious tests in water were gained by studies of resonating air jets.

**Air Facility**

A schematic of the components contained in this facility is shown in Fig. 1. The rectangular plenum supplied air to the nozzle being tested. Pressure in the plenum was controlled by a needle valve in the 30 psi (0.2 MPa) supply line from the air compressor, and this pressure was monitored by a U-tube manometer. Both free jet and impinging jet tests were run, with a movable target plate placed normal to the jet axis at various locations. Perturbations in the jet axial velocity were surveyed with a 25 μm diameter hot film sensor. This probe was mounted on a motor driven rig, allowing a continuous survey along either the axial or radial directions. A nearby microphone monitored acoustic signatures from the nozzle.

The electronic signal from the hot film sensor was conveyed to a Thermo-Systems Model 1050 hot-film anemometer bridge. The output from this bridge was then fed directly to an RMS voltmeter, a spectrum analyzer (Unigon Model 256), and an X-Y plotter. By also sending the RMS voltmeter output to the plotter, side-by-side comparisons could be graphed of the mean, \( V \), and fluctuating, \( u' \),
velocities. Output from the spectrum analyzer was viewed on an oscilloscope, to allow identification of the resonant frequency peaks in the fluctuating velocity. The microphone output was also fed to an RMS voltmeter and to the spectrum analyzer, thus providing a monitor of the frequency and intensity of sound pressure levels. These components were also used to process the signals from the pressure probes used in the water tests.

**High Pressure Cell (HPC)**

The test chamber used to observe the behavior of submerged cavitating jets is shown in Fig. 2. This cell could contain an internal pressure of up to 3,000 psi (20.7 MPa). The cell ambient pressure was controlled by a "choke", a floating double-ended piston valve balanced by nitrogen gas. This floating action allowed for the escape of particles during rock cutting trials. Rock specimens, typically cubes 6 in. (15.2 cm) on a side, were rotated beneath the jet in the HPC at rates up to 66 rpm by means of a variable speed drive.

The high pressure fluid for this cell was usually provided by either a three or a five-plunger pump; if a test required higher flows, then both pumps could be run in parallel. The triplex pump, also rated for drilling mud, will deliver 80 gpm (303 l/m), at 2,000 psi (13.8 MPa). The special quintuplex pump, with changeable plungers and head, can be run over a range;
highest flow: 90 gpm (341 l/m) at 2,500 psi (17.2 MPa), or
highest pressure: 10,000 psi (68.9 MPa) with a 20 gpm (76 l/m)
flow capacity.

For flow visualization and photography, the HPC was fitted
with three circular viewing ports, each 1.5 in. (3.8 cm) in
diameter. A typical photograph of a self-resonating cavitating
jet taken in this cell is shown in Fig. 3. This photograph was
taken by darkening the room, opening the camera shutter, and
releasing a single flash from a stroboscopic light source. When
observing the jets by eye, the strobe was operated at a suitable
submultiple of the jet resonance frequency so as to reasonably
"stop" the motion of the vortices. In this manner, jet structure
could easily be monitored while operating parameters were varied.

Two piezoelectric pressure transducers (PCB Piezotronics
Model No. 101A04; 0.25 in. (6.4 mm) dia.) were mounted in the
HPC. One was placed in the inlet supply pipe feeding the nozzle;
the other in the wall of the main pressure vessel. The same
instrumentation used for the air tests served to process the
signals from these pressure transducers.

JET STRUCTURING OBSERVATIONS

General Test Method

Well over a hundred different organ-pipe configurations
have been investigated, both in air and in water. In these
studies the supply pipes have been similar to those shown in Fig. 7 of [1]. Most have been straight although some have utilized the actual curved extended tubes from SMITH roller bits. Some tests were conducted, in air, with a complete 12½ in. (31.1 cm) diameter SMITH F-3 three-cone bit as shown in Fig. 4, and runs were also made in water using a one-third sector of such a bit.

In all of these tests the procedure involved changing the pressure drop across the nozzle so as to vary the jet velocity (for a fixed ambient pressure when testing in water) and observing the output from the anemometer or pressure transducer. It is generally very easy to observe when the jet becomes structured. If the frequency is in the audible range a pure tone is heard. The oscilloscope output from the anemometer or pressure transducer becomes periodic and grows in amplitude as a particular mode becomes excited. The magnitude of the fluctuating signal is recorded along with its frequency.

**Natural Frequency**

In most of the tests conducted, the observed resonant frequency was within about 10 percent of the frequency which corresponds to multiples of a half wave length. Such a result is expected because the nominal supply pipe to orifice diameter in all of the tests conducted has been two or less. We have applied more
sophisticated analyses [2, 3] to determine the natural frequency for the actual area distributions tested and the agreement with measured frequencies was excellent. However, for preliminary design purposes equation (14) of Ref. [1], which is based on natural frequencies corresponding to standing waves in the tube of half wave length multiples, is adequate.

Fig. 5 compares equation (14) [1] with the results obtained in air, using straight tubes with diameters of 0.6 to 1.2 in. and a nozzle having a critical Strouhal number of approximately 0.45. Some tubes included steps located at antinodes. The agreement is very good between these experimental results and the trends predicted by equation (14) [1].

**Effect of Nozzle Geometry on Critical Strouhal Number**

Fig. 6 illustrates the nozzle features which are being varied so as to determine their effect on the critical Strouhal number. Fig. 7 shows the response in air for a supply tube of length 8.75 in. (22.2 cm), D = 0.81 in. (20.6 mm), and d = 0.4 in. (10.2 mm) with a nozzle having a fixed inlet contour. The solid and dashed curves are for two different exit contours, and the various symbols are for several throat lengths. It will be noted that the critical Strouhal number may be varied by changing such nozzle features.
Fig. 8 shows the measured response in water of an organ-pipe supply tube having $L = 4.3$ in. (10.9 cm), $D = 0.40$ in. (10.2 mm), $d = 0.2$ in. (5.1 mm), and a nozzle with fixed inlet contour. The different curves are for various throat lengths and exit contours. The critical Strouhal numbers for each nozzle are also shown in this figure. Again it is important to note that there is a substantial variation in the critical Strouhal number as the nozzle features are changed. We have tested nozzles having $S_d^*$ as low as 0.28 and as high as 0.9.

Although we have found testing in air to be useful, there are important differences between results obtained in air and in water. These discrepancies were not surprising in view of the seventy-fold difference in Reynolds number.

**Response Width and Amplitude**

Experience has shown that the jet is structured into ring vortices whenever the anemometer or pressure signals become periodic – even when the magnitude of $u'/V$ or $p'/\Delta p$ is only 5 to 10 percent. Figs. 7 and 8 show that the width of the response is approximately $\pm 15$ percent of the Mach number at which the maximum modulation amplitude occurs.

In Figs. 7 and 8 it can be seen that the maximum modulation amplitude decreases as the nozzle features are altered so as to raise the critical Strouhal number. This result is expected
because increasing the Strouhal number corresponds to a reduction in λ, the spacing between the vortices. Thus the circulation strength, Vλ, of each vortex is lower, and the maximum value of u'/V in the jet should decrease.

It was important to be able to vary the critical Strouhal number by changing the nozzle features, so that self-excited systems could be designed despite constraints on the tube length. However, it should be recognized that when there are no length restraints, nozzles should be selected to have the lowest possible Sd*, compatible with jet structuring, so that the circulation strength of each vortex is maximized. In the range of flow conditions presented here the lowest Strouhal number for which optimum structured flow has been observed is approximately 0.25.

Cavitation Inception

The prediction that structured jets should have higher incipient cavitation numbers in comparison to unstructured jets has been confirmed by every test conducted in water. In most cases cavitation was first observed near the boundary, and out several jet radii from the jet axis. Using the curve shown in Fig. 1 of Ref.[1] for conventional drill bit nozzles as a bench mark for incipient cavitation numbers, the measured incipient cavitation numbers for the self-excited structured
jets tested were two to six times higher than this baseline curve. As pointed out previously, almost all of the nozzles being studied had supply pipe to orifice diameter ratios of two or less. Thus the major goal of achieving higher incipient cavitation numbers for nozzles supplied with pipe diameters less than approximately twice the orifice diameter has been achieved.

We have carried out a few tests which have demonstrated the low boundary pressures (and improved bottom hole cleaning) that result when jets are structured. This has served to confirm that very high measured incipient cavitation numbers correlate with a flow pattern which leads to the boundary pressure predictions.

A further observation has been made relative to cavitation. We have observed that many nozzle shapes are capable of self excitation when the operating cavitation number is less than the inception value. However, when $\sigma/\sigma_i > 1$ only a narrow family of nozzle shapes will self excite and structure into vortex rings. We are currently concentrating our studies on this phenomenon.

**ROCK CUTTING TESTS**

Although most of our work to date has been directed toward developing procedures for designing self-excited structured jet
nozzles to be tried in existing mechanical bits, we have carried out several tests to compare the rock cutting ability of unstructured and structured cavitating jets. Fig. 9 shows the dimensions of an organ-pipe configuration used to feed either a standard SMITH Tool nozzle shape or a CAVIJET nozzle, each with \( d = 0.25 \text{ in.} \) \((6.4 \text{ mm})\). These nozzles were tested in the High Pressure Cell at various nozzle pressure drops and ambient pressures.

A typical comparison is shown in Fig. 10 between a self-resonating cavitating nozzle and a conventional SMITH nozzle supplied for use in a roller-cone deep-hole bit. Seen is a top view of one face of a 6 in. \((15.2 \text{ cm})\) cube specimen of Indiana limestone. To allow a half-circle cut to be made by each nozzle, one half of the rock face was protected by a metal plate. The nozzle was then changed, the plate shifted to protect the other half of the cube-face, and the same conditions were run again. In this way, variations due to rock properties could be minimized. Under these conditions, the mean slot depth cut by the ORGAN-PIPE CAVIJET was 4.3 times deeper than that cut by the SMITH nozzle.

Another series of rock cutting tests was made, comparing scale models of the extended tube and nozzle geometry of an existing SMITH roller bit and an early modification designed to
self excite and structure the jet. These models were half-scale as shown in Fig. 11. Table 1 presents some rock cutting data for these two nozzles. Except at the very low cavitation number of 0.067, the ORGAN-PIPE CAVIJET nozzle system cut this limestone to a depth 2 to 2.5 times greater than the standard SMITH system. It is important to note that for the pressure drops (<2,500 psi) (17.2 MPa) currently used in drilling practice, we do not expect the jets to deeply kerf the rock – even with improved nozzle systems under cavitating conditions. However, the more intense excited jets should provide enhanced cleaning of the hole bottom. The rock cutting results presented here are for traversing rates much less than those used in rotary drilling and serve only as a measure of the relative intensity of various designs.

Fig. 3 is typical of photographs taken of cavitation which occurs in the ring vortices of the structured jet created by the CAVIJET model. The rings are generally very coherent for about four diameters and are entirely disrupted after about six diameters. Our observations generally confirm that the vortex convection velocity is about one-half of the mean jet velocity and thus the vortex spacing is between about $d/2S_d$ and $2d/3S_d$.

**DRILLING MUD TESTS**

Full scale tests of ORGAN-PIPE CAVIJET systems, using water and water-based muds with densities up to 14 ppg. (1.7 gm/cm³) were recently conducted in the test loop at the NL Industries
Drilling Systems Technology Laboratory. The results showed no fundamental differences for resonance performance in water or the several muds tested. Tests were made over a wide range of parameters (Mach no., cavitation no., Strouhal no.).

**PLANNED FUTURE WORK**

In this paper we have summarized our progress to date on a program of investigation which is on-going and far from complete. In order to proceed as rapidly as possible in the development of procedures for designing self-excited, ORGAN-PIPE CAVIJET nozzle systems suitable for installation in existing mechanical bits, we have postponed systematic studies of a number of areas—hence complete understanding of some of our observations is presently lacking. Much research remains to be done and should be done.

At this time the system designs are based on model tests conducted in water, usually at model scales of 1/3 to 1/2. We have begun to study how drilling mud affects these results and will continue systematic laboratory tests to gain insights into rheological effects on the phenomena. Such testing will serve to modify the nozzles selected from water tests and to help interpret field results.

To obtain insights into the effect of the ORGAN-PIPE CAVIJET concept, as presently developed, on drilling rates we have designed systems suitable for installation in a three-cone roller bit.
Hycalog and the SMITH Tool Company plan to fabricate some of these modified bits and test them in the field.

CONCLUDING REMARKS

Since any report of a work in progress must contain many unanswered questions, we beg the reader's indulgence and trust that continued efforts now being exerted will allow us to fill in these gaps.

However, several important conclusions are now possible and may be summarized as follows:

1. Using the ORGAN-PIPE CAVIJET concept, self-excited jets can be obtained which structure themselves into periodic ring vortices. This concept is adaptable for utilization in mechanical bits used in current deep-hole drilling.

2. ORGAN-PIPE CAVIJET systems have measured incipient cavitation numbers two to six times higher than those obtained for conventional drill bit nozzles. Thus, bits utilizing self-resonating cavitation effects will have drilling rates influenced at depths two to six times greater than with tools now being used.

These increased values of incipient cavitation numbers are consistent with theoretical predictions and give some credence to the possibility that such structured jets should produce improved bottom hole cleaning, even when operating at depths below where cavitation will exist.
3. The measured natural frequencies of the organ-pipe systems tested correspond to multiples of half wave length standing waves.

4. The response width of self-excited systems is approximately ±30 percent of the design nozzle pressure drop.

5. The critical Strouhal number may be varied by changing details of the nozzle geometry. Thus it is possible to design practical organ-pipe systems for many specified operating conditions.

6. Some nozzle designs which self excite under cavitating conditions do not continue to do so under noncavitating conditions. However, designs have been tested which self excite and produce structured jets regardless of the operating cavitation number.

7. There are some differences in the critical Strouhal number of nozzles tested in air, water, and drilling mud. Rheological effects merit further study, in order to provide optimum resonating designs. Strong jet resonance in moderately dense mud, however, has been achieved.

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REFERENCES


**Fig. 1** Apparatus for nozzle tests with air

- **Air Supply:** 0.2 MPa (30 psig)
- **Needle Valve**
- **U-Tube Manometer**
- **Test Nozzle:** 3.2 to 9.5 mm (1/8 to 3/8 in.) diameter orifice
- **Pressure Tap**
- **Plenum**
- **Moveable Target**
- **Microphone**
- **Longitudinal Traverse:** 1.1 mm/s (0.05 in./s)
- **Anemometer**

**Fig. 2** High pressure cell (HPC)

- **Standoff:** \( X = 12.7 \text{ mm (0.5 in.)}; \ X/d = 2.7 \)
- **Nozzle Pressure Drop:** \( \Delta p = 17.2 \text{ MPa (2,500 psi)} \)
- **Ambient Pressure:** \( p = 3.9 \text{ MPa (560 psi)} \)
- **Nozzle Orifice Diameter:** \( d = 4.7 \text{ mm (0.186 in.)} \)
- **Resonance Frequency:** 20.5 kHz
- **Strouhal Number:** \( S_d = 0.52 \)
- **Cavitation Number:** \( \alpha = 0.22 \)
- **Nozzle:** Organ-Pipe Cavijet®, with two-step pipe configuration. This nozzle is half-scale model of Cavijet® to be used in a three-cone roller bit.

**Fig. 3** Typical photo of ring vortices form self-resonating Cavijet® nozzle. Note vortex spreading across surface of target plate
Three cone bit test in air

Fig. 4

Fig. 5 Relation between Mach number and nozzle length for organ-pipe CAVIJIET® nozzles

Fig. 6 Organ-pipe nozzle features tested to determine effect on critical Strouhal number

Fig. 6

Fig. 7 Effect of variations in nozzle shape on organ-pipe CAVIJIET® resonance in air. Nozzle diameter: \( d = 0.40 \) in.; Feed-tube: curved, in three-cone bit leg, diameter: \( D = 0.81 \) in.; length: \( L_p = 8.75 \) in.

Fig. 7

Fig. 8 Effect of variations in nozzle shape on organ-pipe CAVIJIET® resonance in water. Nozzle diameter: \( d = 0.20 \) in.; Feed-tube: straight, diameter: \( D = 0.40 \) in., length: \( L_p = 4.37 \) in.

Fig. 8