Flameout in Repetitively Pulsed Chemical Lasers

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In an atmospheric pressure, repetitively pulsed, subsonic flow chemical laser, H_2 (D_2) and F_2 gases mixed upstream of the lasing region must remain unreacted until the volumetric initiation occurs. To achieve this, we provided a slug of H_2-free gas flow to isolate the burnt mixture from the incoming fresh mixture by briefly switching off the flow of H_2 between pulses. Fluidic bistable amplifiers were used to do the switching. A switching time of 0.4 msec was obtained. Flameout was achieved at 60 pps with mixtures containing up to 8% H_2 and 30% F_2 (in He) by volume.

Introduction

IN an atmospheric, repetitively pulsed, subsonic-flow chemical laser, H_2 (D_2) and F_2 gases mixed upstream of the lasing region must remain unreacted until the volumetric initiation. For a mixture yielding high electrical laser efficiency[1] (~100%) and high mass utilization (~50 kJ/lb), it is necessary to briefly turn off the flow of either the H_2 (D_2) or the F_2 in order to obtain flameout after each initiation. Increasing O_2 to short-term stabilize this type of mixture or adding flame arresters (such as screens) is not effective, since the shock amplitude from the initiated mixture produces an F-atom concentration on the order of or in excess of the amount desired to efficiently initiate a pulsed chemical laser mixture. It was experimentally found[2] in a large-scale device that mixtures containing an excess of 2.5% H_2 with $[F_2] > [H_2]$ could not be short-term stabilized with O_2 and that after initiation the flame front (detonation wave) propagated upstream with supersonic velocity and remained burning at the H_2-F_2 mixing point as long as the flow remained *on*. Furthermore, for efficient initiation a nonstoichiometric[1] laser mixture with $[F_2] > [H_2]$ is required. It follows that it is highly desirable to turn *off* the hydrogen flow periodically, since it constitutes a fraction ($\approx$2%) of the total mass flow (8% of the total volume flow).

Turning the hydrogen flow off, while the He and F_2 flow continues, creates an uncombustible buffer zone between the burned mixture and the incoming laser gas. Furthermore, for a pulsed laser in general, any gas injected during the time the acoustic disturbance is being damped to levels of the order of $\delta\rho/\rho \approx 10^{-3}$ is not useful as a good optical lasing medium. Therefore, it is desirable to keep the hydrogen flow off during the entire flushing time. This also reduces the average exhaust gas temperature, since the heat release is a function of the volumetric hydrogen flow, bearing in mind that $[F_2] > [H_2]$.

To narrow down the type of method for controlling the hydrogen flow, it must be remembered that a good optical medium homogeneity (uniform index of refraction) throughout the laser region is required at the time of initiation. It was determined[3] that the hydrogen concentration of the active laser volume in a pulsed chemical laser cannot vary in excess of 1% of the total laser mixture. Therefore, from a laser gas utilization point of view, only that portion of the laser gas for which the flow rate is constant is of any use. The gas which enters the laser during the time the hydrogen flow turns on or off is useless, since it does not meet the medium homogeneity requirements. It follows that both the turn-on and turn-off period must be a small fraction of the laser interpulse duration. Therefore, it appears that fast mechanical valves (such as those in use for combustion engines), opening and closing at the desired repetition rate, must be ruled out for repetition rates as low as 50 pps, since the time period during which a completely uniform mass flow is obtained is only a fraction of the interpulse duration. Furthermore, even if mechanical valve technology could be improved to meet the foregoing system requirements, it appears that a mechanical valve system would be highly unreliable, since hundreds of valves are required, and only one malfunctioning valve would render the laser useless. For this reason, we abandoned mechanical valves in favor of a technique that has no moving parts. Of the various methods considered for nonmechanical control of hydrogen, two look attractive. We believe that the use of controlled fluidic devices best meets the system requirements for pulsed chemical lasers.

We chose nonvented bistable fluidic amplifiers to control the hydrogen flow because of their simplicity and precise control. Switching time from 0 to 100% of the flow can be much less than a millisecond. These devices have no moving parts, and their size for these applications is such that small dust particles cannot plug up the power jet or control ports. It follows that they should be extremely reliable, while their lifetime should be practically infinite.

II. Experimental Apparatus

A small-scale experiment to demonstrate flameout for repetitively initiated conditions was constructed. The gas used for the test is of high fluorine and high hydrogen concentration, a mixture of interest for atmospheric pressure, room temperature, pulsed chemical lasers. The laser gas flow cross section was 10×10 cm, surrounded by an equally dense N_2 and He boundary flow 3 cm in width. The flow velocity was selected such that a 30-cm-long cavity was filled with a hydrogen containing mixture, while the flushing or hydrogen-free gas slug 15 or 30 cm in length was used to separate the burned laser gas from the fresh, incoming laser mixture. The maximum flow capability was consistent with a 60-pps repetition rate. The laser gas contained up to 30% F_2 and 8% H_2. The diluent gas was helium. Oxygen, at 1/25 of the flourine concentration, was added for long-term mixture stabilization. The boundary flow velocity was adjusted to equal the laser gas velocity to minimize mixing and prevent the laser mixture from being ignited from the flow channel wall. The gas supply system was designed for a run time of 500 msec.

A mixer was constructed to blend the H_2 and F_2 containing gases "on the fly." The final mixing must be performed at atmospheric pressure. Premixing at high pressure and injection into the laser cavity through sonic orifices, such as in a pulsed electric laser, must be ruled out, taking into con-

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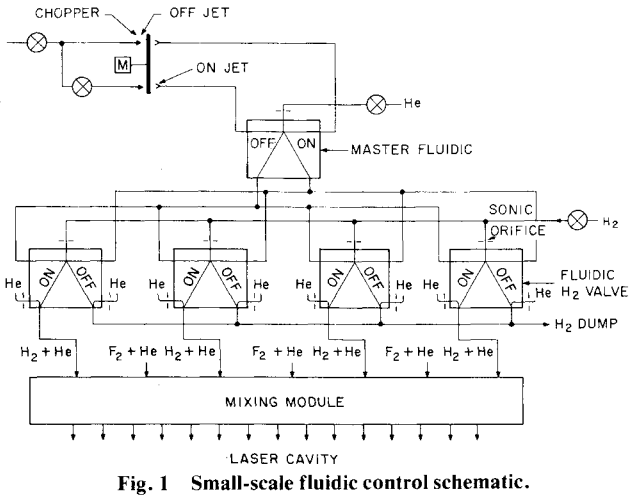

Fig. 1 Small-scale fluidic control schematic.

sideration the long-term laser mixture stability. The gas temperature of 300 K was used to perform the flameout test, since the laser output for an atmospheric mixture in the temperature range of 280 to 300 K is optimum. Furthermore, since at the time of initiation the gas contained upstream of the active laser region and in the mixer cannot be utilized, it is necessary to minimize the mixer volume. This is necessary to maximize the mass utilization and power output.

The mixing was performed between parallel stainless-steel plates. The flow condition, mixing length, and plate separation were selected similar to a turbulence tube mixer described elsewhere.[2]

The hydrogen flow control is shown schematically in Fig. 1. Four unvented bistable fluidic amplifiers control the hydrogen flow. When the fluidic amplifiers are on, hydrogen is injected into the mixer, yielding a combustible laser gas composition with 8% H_2. With the fluidic amplifiers switched to the other bistable position (off) the hydrogen is dumped, yielding an uncombustible gas mixture. The precise hydrogen mass flow of each fluidic device is controlled independently of the laser cavity pressure with the use of four matched sonic orifices, one for each fluidic device. They are located upstream of the hydrogen fluidic power jet. The power jets are usually operated with 100% H_2, with the exception of some initial tests where the power jet was diluted with helium to yield a lower H_2 containing laser mixture, while the fluidic amplifiers were operated in the desired power jet pressure range. A set of helium orifices is located in the hydrogen *on* port. The amount of injected helium gas is such that usually a H_2:He mixture of 16:84 is obtained. This constitutes the hydrogen gas mixture. The flourine gas mixture of F_2:He:O_2, of equal volumetric flow rate, was premixed and was continuously injected into the mixer.

A small amount of helium was also injected into the fluidic amplifier's *off* port. This was necessary, since during the on period a small amount of gas is sucked back out of the hydrogen dump line. Since this gas can be contaminated, the injected helium rate with a mass flow slightly in excess of the *off* port entrainment assures that a clean and precisely metered hydrogen mass flow is injected into the mixer. This way the hydrogen mass flow into the mixer is identical to the mass flow of the hydrogen power jet injection orifices.

A master fluidic amplifier, identical in construction to the hydrogen fluidic amplifiers, however without the helium injection into the output ports, is used to slave the four hydrogen devices. The master was operated with helium. The power jet pressure was selected so that the output characteristics of the master were optimized with the input of the four slaves.

There are many available techniques for driving the master amplifier. For instance, it can be connected either as a self-oscillator or driven by another bistable oscillator with adjustable frequency and on/off periods. We elected, out of convenience, to drive the master with two jets, interrupted alternately by a chopper wheel rotating at the desired rpm (3600 or 1800). Two modes of operation were tested. With the first mode, the jet receiver delivered a pressure pulse only long enough to switch the device, using the bistable nature of the master to keep the device in the desired state. A control pulse of less than 1 msec was required to facilitate switching. However, most of the testing was performed with the two jets interrupted alternately, with either one of the receivers on all the time. The chopper wheel consisted of two thin slotted disks in contact with each other. Rotating one disk in relation to the other allowed adjustment of the on to off period. This system was used to adjust the hydrogen on time from 50 to 70% of the interpulse duration.

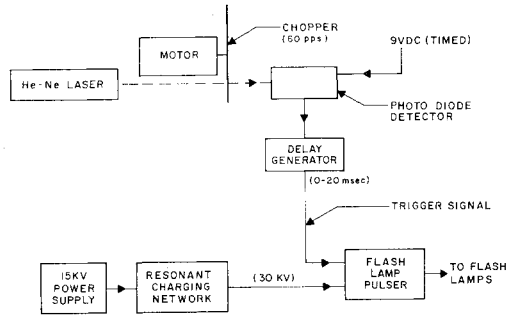

Fig. 2 Electrical schematic.

The chopper wheel control of the master, instead of a fluidic timing device, was used to simplify synchronization of the hydrogen flow with electrical initiation. Figure 2 shows the schematic for the initiation. A chopper wheel was also used to interrupt a CW He:Ne laser beam. The timer was used to control the 9-V dc power for the photodiode. This controlled the overall duration run of the flashlamps. The output of the photodiode was fed to a delay generator. The delay generator allowed triggering of the flashlamp pulser at any time relative to the fluidic cycle. Two 10-cm-long lamps, located outside of the laser cavity were used to initiate the laser mixture. They were powered by a pulser with resonant charging. An output energy capacity of up to 200 J/pulse could be obtained with a repetition rate of up to 200 pps. For the typical run duration of 0.5 sec, no lamp cooling was necessary. The electrical lamp connections were of low inductance, such that a lamp output of pulse length less than 1 μsec was obtained. The two lamps were mounted with reflectors on two opposite sides of the flow channel. Quartz windows with a thickness of 0.25 in. were used to transmit the flashlamp light.

The laser exhaust was scrubbed by a charcoal filter to burn up the excess flourine, while a soda lime bed served as the HF filter. The filtered gas, containing mainly helium, was exhausted to atmosphere. The pressure drop through the filters was a small fraction of a psi, allowing us to perform the flameout test at atmospheric pressure. For these tests, no acoustic absorber material was used to attenuate the overpressure. It follows that the flameout test was performed under the most severe condition. Both the mixer and laser flow channel were constructed out of stainless steel.

III. Diagnostics

For the flameout diagnostics we used CW uv light to minitor the flourine concentration at two different locations along the gas flow direction. The two probing points were 5.5 and 30.5 cm, respectively, downstream of the mixer. As a light source we ordered a 1-mW CW feedback stabilized He:Cd laser. However, due to its slow delivery time, most of the data were collected using the 253.7-nm line of two Hg:Ar pin lamps. Sapphire was used for windows. The transmitted light was passed through a 253.7-nm filter and monitored by

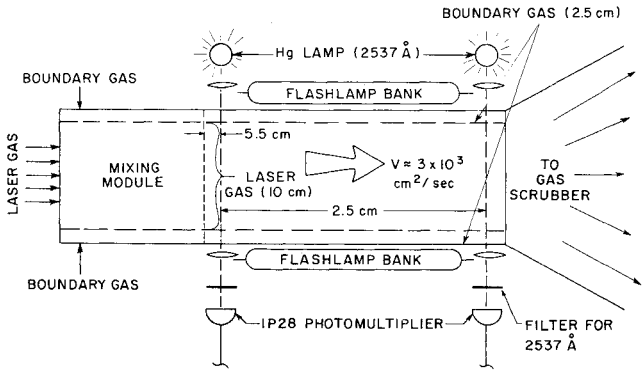

Fig. 3 Small-scale flameout schematic.

RCA 1P28 photomultipliers, as schematically shown in Fig. 3. This technique allows determination of the hydrogen front arrival, since the fluorine mixture is being diluted by the hydrogen flow. Furthermore, a large and unmistakable change in the absorption signal is obtained when combustion occurs, since part of the F_2 is burned while the remaining concentration is lowered by the expansion as a result of the heating.

Two crystal pressure transducers are mounted flush with the flow wall to obtain the time of explosion and the reverberation of the pressure wave. A total of eight strain gages are also used to monitor the pressure and turn on of the various gas supplies and the fluidic switching. All fast signals are recorded on oscilloscopes, while the strain gage and timing signals are monitored on a Visirecorder.

IV. Fluidic Amplifier Development

From a system consideration, unvented bistable fluidic amplifiers were selected to control the hydrogen flow. These devices were designed so that a turbulent jet issuing from a nozzle attaches to one sidewall or the other, in a stable manner. Control ports located at right angles to the supply nozzle were used to switch the power jet from side to side. These devices have no moving parts. They switch in a few flow times, and have a slight suction rather than a leakage at the *off* port to assure a constant hydrogen flow into the mixer.

As a point of departure, we chose the modeling work of Drzewiecki.[4] It should be noted that this model, like others, assumes low Mach numbers and a device with control and outlet ports vented to atmosphere. For the present application, it was desirable to operate the power jet at sufficient pressure to allow pressure recovery of several psi, in order to overcome the hydrogen flow pressure drop through the mixer. We also desired to use the smallest possible nozzle size, so as to reduce the switching time. As a result, the flow is probably sonic and underexpanded leaving the nozzle. The interaction of such a flow with nearby walls is not easy to model.

It was expected that the predictions of the model would not apply exactly in this case. We adopted the philosophy of using the model as a basis for constructing a device where some of the dimensions, such as the sidewall and splitter-plate locations, could be adjustable so that a good operating point could be found experimentally. Once a good working unit was obtained, we scaled the height of the device to obtain the desired hydrogen mass flow.

Input and output characteristics were obtained from the original unit with various splitter-plate positions and sidewall configurations. With the final test unit the splitter plate and sidewalls were adjusted with a micrometer. This was necessary in order to assure the correct performance of the fluidic amplifier in the desired system configuration. From these data, too numerous to be stated here, it was determined that one bistable master amplifier is sufficient to slave four similar devices with unloaded outputs. By loading the output, to simulate typical service conditions, it was determined that a fan-out of four appears conservative. Figure 4 shows schematically the pertinent dimensions of the master fluidic amplifiers being used in the flameout test unit assembly. The entire device was made of Lucite. Figure 5 shows some of the test results with the fluidic master amplifier connected as a self-oscillator. As can be seen from the hot-wire output, the device switches in less than a millisecond, while operating at about 370 pps. These tests are performed using helium with the hot wire located near the output port. Figure 6 shows the fluidic amplifier switching as part of a system in the assembled flameout device. Hydrogen was used as the gas in the power jet. In this case, the hot wire was placed directly into the flow *off* port of the fluidic amplifier. The switching occurs in about 0.4 msec. This performance is far from being optimized. However, it meets completely the present program objective. It further appears that, if necessary, the fluidics technology can be extended to much shorter switching times and much higher repetition rates.

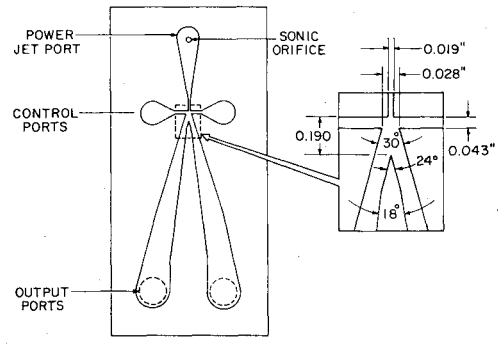

Fig. 4 Master fluidic amplifier.

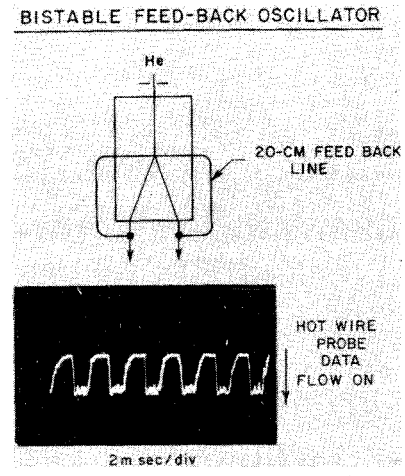

Fig. 5 Bistable fluidic amplifier connected as 370-pps self-oscillator.

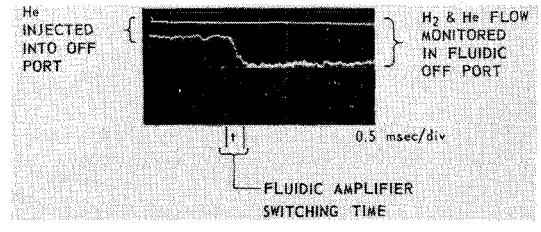

Fig. 6 Fluidic amplifier switching time measurement with hydrogen gas in power jet.

V. Flameout Results

From both the pressure signals and the flourine absorption signals it can be determined when flameout has been obtained. Figure 7 shows a simplified X-T diagram for the condition of flameout. It also shows qualitatively the type of photomultiplier (PM) output signal. If flameout is not ob-

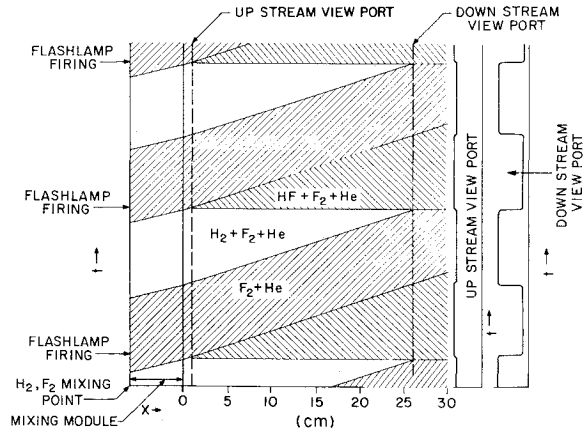

Fig. 7 *X-T* diagram for flameout.

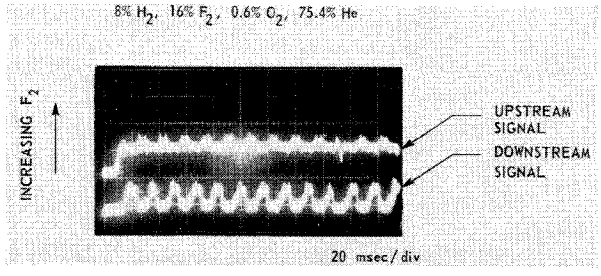

Fig. 8 Flameout with 16% F_2, 8% H_2 at 60 pps.

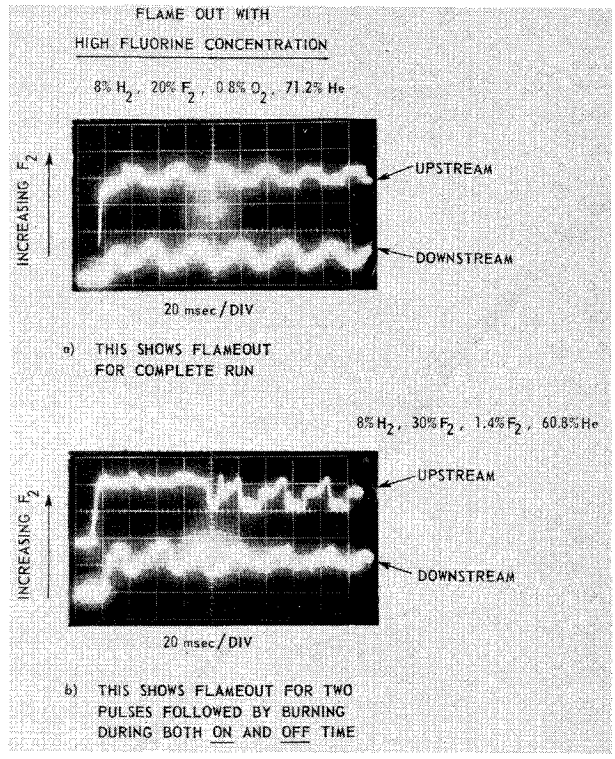

Fig. 9 Flameout test: a) 20% F_2, 8% H_2; b) 30% F_2, 8% H_2.

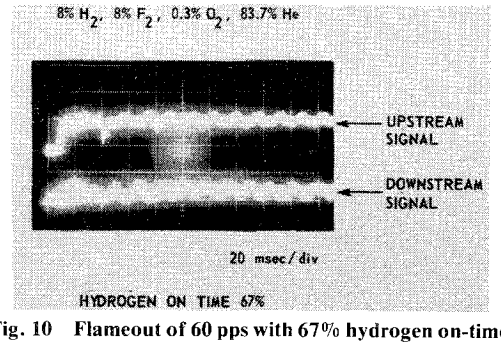

Fig. 10 Flameout of 60 pps with 67% hydrogen on-time.

tained, the timing and output level of the PM signal are significantly different; specifically the upstream signal, since in the correct mode of operation of the upstream fluorine density is always high and the level of light signal change is small.

Figure 8 shows a typical run for a mixture of 10% F_2 and 8% H_2 at a repetition rate of 60 pps. As can be seen, the burned mixture appears downstream, while no burning occurs upstream. This, as in most other runs, extended over a time of 500 msec. Figure 9a shows the flameout for a mixture of 20% F_2, 8% H_2 at 60 pps with more details. Figure 9b was included to illustrate a run where burning did not occur with a mixture of 30% F_2, 8% H_2. With this run, burning occurs during the time the hydrogen flow is supposed to be off. The cause has been diagnosed as incorrect back pressure, at the *off* port, and as negative reflection of the shock waves off the cold-hot gas interface located downstream in the exhaust region. Initially, the shock wave was reflected at this interface with a negative polarity and an amplitude of about -3 psi. When this disturbance appeared at the *on* port of the hydrogen fluid, the off-biased condition could not be maintained until the pressure subsided. A burst of hydrogen was momentarily injected into the mixer and ignition occured as the $H_2 + He$ and $H_2 + F_2$ mixed. With the change of the exhaust duct cross section, such that the negative wave amplitude was reduced, this effect was eliminated. With this modification, flameout with mixtures up to 30% F_2, 8% He was routinely obtained.

For a pulsed chemical laser with an efficient acoustic absorber installed, this type of problem would not occur, since the reflected shock wave produced by the chemical reaction must be reduced by several orders of magnitude in order to meet the optical medium homogeneity requirements ($\delta\rho/\rho \lesssim 10^{-3}$). Therefore, the fluidics will always see an almost constant backpressure during the hydrogen on time. As long as the backpressure variation remains much less than ± 0.6 psi for the tested fluidics, the hydrogen supply to the mixer will remain 100% constant, identical to the amount of gas metered by the sonic orifices upstream of the power jets. The first shock wave, shortly after the initiation or any other positive reflections during the hydrogen off period, does not cause any problems, since at this time the fluidics are biased off and the overpressure has no effect in changing its state.

The preceding flameout tests were performed with a hydrogen on time identical with the off time. This would allow a gas utilization of only about 50%. To demonstrate a larger gas utilization potential we reduced the hydrogen off time to 33% of the interpulse duration by reducing the hydrogen-free gas slug from 30 cm to 15 cm. The hydrogen containing gas, initiated per pulse, remained at 30 cm. Figure 10 shows the test result at 60 pps. As can be seen, flameout is obtained for a flow condition where 67% by volume may be utilized. To increase the gas utilization further appears to be possible. However, it remains to be shown that the acoustic disturbance can be quieted down in time, where the hydrogen off time and the acoustic damping time are the determining factors in the gas utilization efficiency.

The data shown in Fig. 10 were selected to demonstrate the recoverability of the system. As can be seen on the upstream trace, preignition and burning in the mixes did occur 30 msec after the fluorine turn-on time. However, at the next hydrogen injection the system recovered to the normal mode of operation. This is of importance for larger systems where the probability of preignition is larger.

VI. Conclusion

The use of fluidic devices appears to be an excellent method for achieving flameout in a repetitively pulsed chemical laser. Fast switching, high repetition rate, high reliability, and low cost of fabrication of fluidic amplifiers appear to meet the overall system requirements. The demonstrated flameout at up to 60 pps and volumetric gas utilization of 67% has not in any way taxed the fluidic technology. The measured switching time of 0.4 msec from full off to full on, and vice versa, can be expected to be increased by over one order of magnitude, if desired. The demonstrated switching rate of 370 pps can be extended to a pulse repetition frequency in the kilohertz. It can be expected that, far below this type of performance, other elements of the pulsed chemical laser system (such as the mixer, acoustic damping techniques and the laser flow velocity through the cavity) will limit the pulsed chemical laser repetition rate.

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