AIAA Journal
Vol. 46, No. 4, April 2008

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Acoustic Response of a Resonant Igniter with Confuser Inlet

Nicholas Pearson* and William E. Anderson†
Purdue University, West Lafayette, Indiana 47907

DOI: 10.2514/1.22340

I. Introduction

RESONANCE tubes, conceptualized by Hartmann [1], have been used as nonmechanical ignition devices since their adaptation into heat sources by Sprenger [2]. The operation mode of a resonance tube is well understood. High temperatures are rapidly achieved when the tube is excited with an underexpanded high-velocity gas jet, placed a short distance from the open end. In this configuration, the jet compresses the gas in the tube, producing a shock that propagates along the length of the tube and reflects off of the closed end. The shock returns to the tube entrance, pushing the jet back from the tube and allowing the gas in the tube to decompress and exit. The subsequent expansion wave propagates along the length of the tube and reflects off of the closed end. When the expansion wave reaches the entrance of the tube, the gas jet reenters the tube to start another compression cycle [3]. This propagation and reflection of the shock wave allows for rapid heating of the resonance tube.

A model of this form has been proposed by Kessaev [4]. In his model, it is assumed that there is no mixing between the incoming gas jet and the gas that is already within the resonance tube. This contact surface between the two gas phases is assumed to act as a piston that is independent of the shock wave. The shock wave precedes the contact surface as they travel down the length of the tube. After reaching the closed end of the resonance tube, the shock reflects and travels back toward the still-incoming contact surface. When they meet, the incoming contact surface is halted, and the increased pressure causes the gas in the tube to exhaust, expanding isentropically. This model will overpredict the maximum heat-up, but does agree well with the experimental heat-up rate.

This regurgitant mode of operation is expected to have a frequency corresponding to the quarter-wavelength of the tube, as has been shown both experimentally and computationally [5]. A much higher frequency of oscillation, the screech mode, is also possible. In this mode, a nearly normal shock is formed at the mouth of the resonance tube and oscillates at a frequency much higher than the quarter-wave. The operation mode of the igniter can be controlled through use of a trip wire or needle, or by altering the design spacing between the underexpanded nozzle and the resonance tube. A needle is needed to trip the core of the gas flow, causing a pressure loss at the boundary of the needle to avoid the jet-screech oscillation mode [6]. The required physical spacing between the nozzle and a cylindrical resonance tube corresponds to the Mach diamond pattern and is well known [7,8].

Optimum dimension ratios for resonant igniter design have been experimentally determined by previous research. Sprenger [2] began the studies by varying geometric ratios of simple cylindrical resonators and examining the effects on pressure oscillations and temperatures. Kawahashi et al. [3] built on this work by varying geometrical parameters of a single-step tube, which has a larger diameter at the inlet than at the capped end. As the ratio of the length of the small-diameter section to the length of the large section increases, the frequency of the pressure oscillations is seen to increase until it reaches an unstable point. Increasing the length ratio further causes third-mode oscillations to be excited instead of first-mode, causing a loss in heating capacity. As the ratio of the larger tube diameter to the smaller diameter after the single step increases, the oscillation frequency decreases, but does not change mode of excitation. As the incoming jet Mach number increases, the oscillation frequency slightly decreases.

Resonance tubes with conical entrance sections have been suggested by previous research, but data are lacking. A conical design could provide better heating capability than those with a simple cylindrical or step-cylinder shape, because this change would increase the Mach number at the entrance of the cylindrical section. However, design guidelines for frustoconical resonance tube operation need to be explored. In this work, we determine the optimum spacing between the nozzle and resonance tube, as well as the optimum operating ratio between the pressure in the nozzle P_n and in the spacer ring P_o. The final guidelines determined for good operation of cylindrical resonance tubes are outlined in a patent held by Kessaev et al. [7] and are used as a starting point for our design of the igniter. We examine the acoustic and thermal response of our frustoconical resonance tube for a range of pressure drops, $12 > P_n/P_o > 6$, across the nozzle and for varying jet-to-resonance-tube spacings.

II. Experiment

Previous studies of resonance tubes focusing on the operation of forward-facing step design have shown that the heating rate depends highly upon the distance between the jet inlet and the resonance tube. The correct design guideline for this parameter in frustoconical resonance tubes has not yet been well established and was thus the initial determination of this work. Also of interest were liquid fuel ignition testing, verification of nitrogen vs helium operation, and atomization studies. The focus of testing for this article is a comparison of the igniter operation mode as a function of pressure drop across the nozzle.

Our igniter (Fig. 1) consists of four parts: an underexpanded nozzle, a spacer ring, the resonance tube, and an insulating sheath. The nozzle delivers nitrogen or helium gas flow and contains a coaxial capillary tube that functions both as a trip wire to destabilize the core of the gas flow and as a fuel atomization system. Atomization occurs through aerodynamic shear forces followed by catastrophic droplet breakup in the shock system. The spacer ring keeps the optimum physical distance between the nozzle and resonance tube for regurgitant-mode excitation. This spacing is

Received 8 January 2006; revision received 13 February 2007; accepted for publication 22 February 2007.

*Graduate Student, School of Aeronautics and Astronautics. Member AIAA.

†Assistant Professor, School of Aeronautics and Astronautics. Member AIAA.

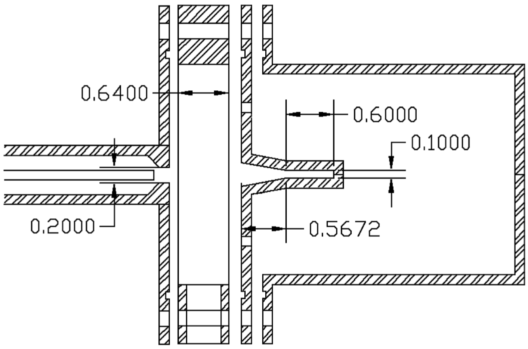

Fig. 1 Resonant igniter design. The four components are (left to right) an underexpanded nozzle for gas delivery with concentric fuel delivery capillary acting as a trip wire, a spacer ring, the resonance tube, and an insulation cap. An unshielded thermocouple is located at the end of the resonance tube, allowing measurement of the stagnation temperature during operation. All dimensions are in inches.

adjusted over a test series for confirmation of the design. The resonance tube contains a tapered conical section that ends in the typical cylindrical shape. An unshielded thermocouple at the resonance tube end cap measures the stagnation gas temperature during testing. The insulating sheath fits over the resonance tube to prevent convective losses to the surroundings, but in testing it showed to provide no benefit.

For each test, a 10-liter gas plenum is pressurized with nitrogen or helium. The plenum is pressurized to 750 psia (50 atm), then exhausted through the nozzle into the resonance tube, allowing a maximum test duration of 30 s. The temperature of the gas at the stagnation point in the resonance tube is measured as the pressure decreases. For ignition and atomization tests, fuel is flowed through the capillary at the proper rate to maintain a mixture ratio within flammability limits. During acoustic tests, no fuel is present.

Acoustic data are gathered with a high-frequency-response microphone located 10 ft from the igniter. Because of this setup, we are limited to determination of the acoustic spectra only; absolute measurements of acoustic power will not be reliable due to potential errors induced by the surroundings, but general comparisons can be made. Data for each test are recorded, divided into 1-s subsets, analyzed by Fourier transform, and presented as power spectra.

III. Results

As the gas plenum exhausts into the resonance tube through the underexpanded nozzle, either the jet-regurgitant or jet-screech mode of the igniter should be excited, depending upon the pressure drop across the nozzle [8]. Rapid heating of the internal gas is measured and presented in Fig. 2. Heating in both cylindrical and single-step resonant tubes is known to show a rapid heat-up to a maximum temperature. For this igniter with the conical confuser input, the initial heat-up reaches a plateau at a temperature 260°F below maximum capability. After the pressure ratio P_n/P_o decreases beyond 8.4, the mode of operation of the igniter changes to the regurgitant mode, heating the igniter to a temperature sufficient for ignition of most hydrocarbon fuels. The pressure ratio at which we observe the peak temperature is higher than for cylindrical resonance tubes [8].

Table 1 shows the temperature at the end cap of the resonant igniter and the corresponding experimentally measured peak acoustic oscillation frequency for a range of pressure ratios across the nozzle. The nominal quarter-wave frequency for our igniter geometry is 4030 Hz at a uniform internal temperature of 300 K, but we expect the experimental frequency to be slightly lower because the actual oscillation length will be longer than the resonant tube. This phenomenon has also been noted in previous work by Kessaev et al. [9]. As shown in Table 1, the actual peak wavelength is initially over 6100 Hz. This high frequency shows that at the high-pressure ratios, operation is in the jet-screech mode.

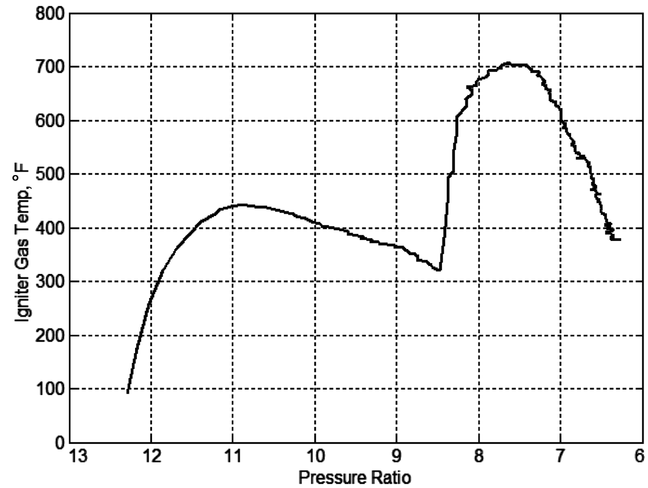

Fig. 2 Temperature at the igniter end cap during a nitrogen test. A gas plenum is allowed to discharge through the igniter. Initial resonance is unable to sufficiently heat the igniter, showing a peak temperature of 442°F. Once the pressure ratio across the nozzle decreases beyond 8.4, the character of the resonance changes. A temperature rise to 702°F is attained.

As can be seen in Fig. 3, this high-frequency peak descends to a lower frequency as the pressure ratio begins to decrease. This effect is a result of the decrease in temperature causing a lower sonic velocity. At a pressure ratio of 8.4, the screech mode suddenly shifts to an oscillation at 3300 Hz. The igniter is now operating in the regurgitant mode at its fundamental frequency. The intensity of the regurgitant oscillation is stronger than the screech mode, which is expected from numerical analyses [6]. The first harmonic overtone is also detected. With jet-regurgitation excitation, the temperature in the igniter is able to rapidly achieve its full potential of over 700°F.

A sudden change from screech to regurgitant operation has been noted by other researchers for a cylindrical resonance tube. Sarohia and Back [8] reported a similar change in operation mode in their work using a 2.54-cm-diam resonant cylinder. The mode change occurred at a pressure ratio of 3.9 across the nozzle. This ratio placed the free jet shock near the resonant tube inlet. This suggests that a similar phenomenon is occurring with our igniter as the pressure drop changes, yet a broadband response during screech-mode oscillation is typically expected. For these flow conditions, we find a single frequency dominates the screech mode.

The spacing between the nozzle and the resonance tube is a design parameter to which proper operation of a resonance tube is particularly sensitive. For frustoconical resonance tubes, the

Table 1 Frequency of maximum acoustic response and gas temperature in igniter as a function of pressure ratio across the nozzle

P_n/P_o	Temperature, °F	Frequency, Hz
11	438.7	3543
10	412.1	6145
9.3	377.4	5790
8.8	352.8	5509
8.4	381.2	5376
8.1	656.3	3345
7.9	693.6	3308
7.6	705.8	3263
7.4	702.4	3193
7.3	681.6	3103
7.1	642.7	2964
7.0	608.2	2937
6.9	568.9	2899
6.8	537.0	2868
6.7	519.2	2872
6.6	488.3	2871
6.5	455.3	2963

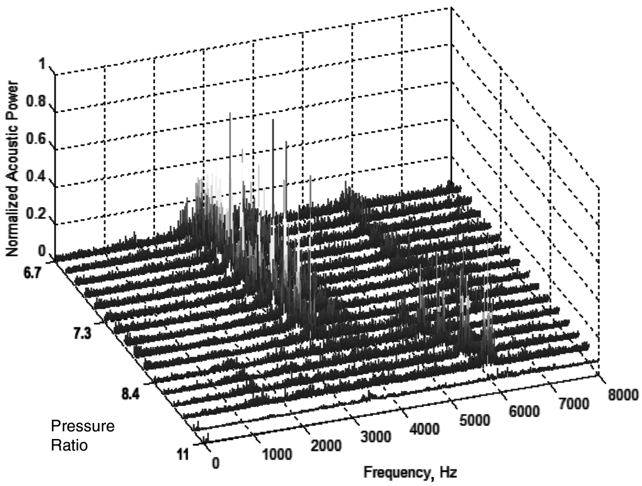

Fig. 3 Acoustic spectra for a nitrogen test corresponding to pressure ratios in Table 1. Frequencies up to 8000 Hz are considered for 1-s sound samples throughout one 20-s test. At high-pressure ratios, the oscillation frequency in the resonant tube shows maximum power near 6000 Hz. At pressure ratios below 8.4, the igniter reverts to the expected regurgitant operation, with peak oscillation near 3100 Hz.

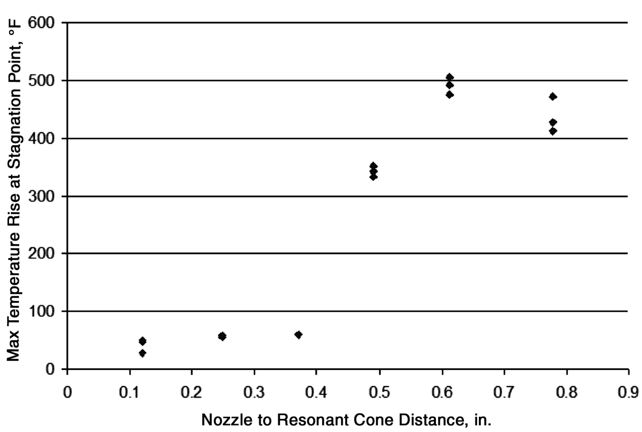

Fig. 4 Effect of spacing between gas nozzle and resonance tube confirms that the guidelines for design set by Kessaev for single-step tubes holds true for frustoconical designs. A spacing of 0.62 in. in accordance with these guidelines does show the greatest performance.

suggested spacing is in the range of 1.5 to 3.2 times the nozzle orifice diameter [7]. To verify this, a total of 18 nitrogen tests were performed with six different spacings between the nozzle and resonance tube. The maximum temperature attained for each test is plotted against the spacing in Fig. 4. It is clear that our original design spacing of 0.62 in., a factor of 3.2 times the nozzle orifice diameter, provides the maximum igniter temperature.

IV. Conclusions

A resonant igniter with a confuser input was designed for the purpose of demonstrating ignition capabilities of resonance tubes with certain hydrocarbon-based fuels. During regurgitant-mode heat-up of the igniter, temperatures over 700°F are attainable using nitrogen as the carrier gas.

The original design spacing of 0.62 in. between the gas nozzle and the resonance tube has been confirmed as the optimum distance, as is shown in Fig. 4. This corresponds to the upper limit of the dimensions suggested by Kessaev [7] for best operation of a resonance tube.

At large pressure drops across the nozzle, a jet-screech mode of oscillation is seen. At our flow conditions, the character of the screech mode differs from previous research. We see a single dominant frequency of oscillation as opposed to broadband frequency excitation. This oscillation is precluded from being a harmonic of the regurgitant mode due to its frequency.

At pressure ratios across the nozzle below 8.4, the intended regurgitant mode of the igniter is excited. The pressure ratio at which the mode change occurs is higher for a frustoconical resonance tube than for cylindrical or single-step designs. The regurgitant mode shows higher acoustic power than the screech mode, in agreement with numerical models. The regurgitant mode oscillates at a frequency slightly lower than the quarter-wave frequency of the resonance tube, as expected. Heat-up of the igniter during the regurgitant mode is satisfactory for hydrocarbon ignition studies, but the high-pressure ratios across the nozzle should be avoided.

Acknowledgment

Support for this work is graciously provided by the U.S. Air Force Research Laboratory.

References

[1] Hartmann, J., "Construction, Performance and Design of the Acoustic Airjet Generator," *Journal of Scientific Instruments*, Vol. 16, No. 5, 1939, pp. 140–149.

[2] Sprenger, H., *Ueber Thermische Effekte in Resonanzrohen*, Vol. 21, Federal Inst. of Technology, Zurich, 1954, pp. 18–35.

[3] Kawahashi, M., Bobone, R., and Brocher, E., "Oscillation Modes in Single-Step Hartmann-Sprenger Tubes," *Journal of the Acoustical Society of America*, Vol. 75, No. 3, 1984, pp. 780–784.

[4] Kessaev, K., "Ignition of Non-Hypergolic Propellants," *48th International Astronautical Federation (IAF) Congress* [CD-ROM], Conference Proceeding Series, AIAA, Reston, VA, 1997.

[5] Hamed, A., Das, K., and Basu, D., "Numerical Simulation of Unsteady Flow in a Resonance Tube," AIAA Paper 2002-1118, 2002.

[6] Xia, G., Li, D., and Merkle, C. L., "Effects of a Needle on Hartmann-Sprenger Tube Flows," AIAA Paper 2003-3888, 2003.

[7] Kessaev, K., Zinoviev, V., and Demtchenko, V., "Acoustic Igniter and Ignition Method for Propellant Liquid Rocket Engine," U.S. Patent No. 6,199,370 B1, 2001.

[8] Sarohia, V., and Back, L. H., "Experimental Investigation of Flow and Heating in a Resonance Tube," *Journal of Fluid Mechanics*, Vol. 94, No. 4, 1979, pp. 649–672.

[9] Kessaev, K., Vidal, R., and Niwa, M., "Gas Jet Release Inside a Cylindrical Cavity," *International Journal of Heat and Mass Transfer*, Vol. 46, No. 10, 2003, pp. 1873–1878.

S. Aggarwal
Associate Editor