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A LABORATORY SCALE SUPERSONIC COMBUSTIVE FLOW SYSTEM

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Abstract

A laboratory scale supersonic flow system [Combustive Flow System (CFS)] which utilizes the gaseous products of methane-air and/or liquid fuel-air combustion has been assembled to provide a propulsion type exhaust flow field for various applications. Such applications include providing a testbed for the study of planar two-dimensional nozzle flow fields with chemistry, three-dimensional flow field mixing near the exit of rectangular nozzles, benchmarking the predictive capability of various computational fluid dynamic codes, and the development and testing of advanced diagnostic techniques. This paper will provide a detailed description of the flow system and data related to its operation.

Introduction

Establishing accurate propulsive system exhaust signatures through computational fluid dynamics (CFD) based predictions requires that the code's models are rigorously benchmarked by comparison to a credible data base of nozzle flow field properties. Many existing signatures codes have their origins in the development of high specific thrust engines and were benchmarked by comparison to measured thrust values and not by the actual physical properties of the exhaust flow field^{1,2}. Thus, high fidelity measurements are required which are established under the controlled conditions achievable in a ground test facility. A laboratory scale supersonic flow apparatus has been assembled which allows the detailed study of high speed flows that contain products typical to common propulsive systems.

To date, three nozzles have been tested in the Combustive Flow System. The first was a rectangular converging-diverging nozzle with an aspect ratio of 15:1. The design Mach for this nozzle is 2.6. Two other nozzles are currently being investigated; an axi-symmetric one designed for 1.5 Mach, and a rectangular nozzle with a 4:1 aspect ratio for 1.5 Mach.

The size and location of the system allows for ready access to the generated flow fields with advanced optical diagnostics and other conventional diagnostic techniques.

Our comparison of measured flow field phenomena to CFD code predictions has been achieved by the testing of a two-dimensional planar nozzle. The primary focus of the current study has been to verify CFD results and correlate these results to experimental investigations involving chemistry. This paper will provide a description of the Combustive Flow System and a brief overview of CFD comparison.

System Description

The Combustive Flow System has been designed to study high stagnation temperature (up to 400° C), supersonic flows which contain products typical of gas and liquid fuel combustion. A schematic illustrating the primary system configuration is shown in Figure 1. Photographs depicting the operational laboratory structure are presented as Figures 2 through 5. The CFS represents a laboratory-size flow system which uses a conventional gas and oil Eclipse Model 82MVTA-PLA burner as an enthalpy source.

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Total enthalpy rates of 15 kw are typical in our experiments. Depending on flow requirements, the system can operate in a continuous or quasi-steady state blowdown mode. A brief description of the various components comprising the system follows.

The installed combustion system includes a nozzle-mixing burner which can be used with combinations of several gaseous and liquid fuels including natural gas and kerosene. Utilizing preheated or non-preheated air, this burner can operate fuel rich, on-ratio (stoichiometric), or fuel lean (excess air). Combustion air is supplied by a separate blower dedicated for this purpose. The burner has a thermal output ranging from approximately 14 kw to 147 kw. Primary ignition is accomplished through a spark-initiated pilot flame. The burner is designed to operate at near neutral pressure differential. An integrated control panel provides for stand-off operation, and numerous safety interlocks are incorporated into the system.

The combustion chamber, or "firebox" is a stainless steel, cylindrical vessel designed for primary flame containment. Deformable metal or graphite compound seals are utilized to provide high temperature compatibility. A multi-port design allows for visual flame monitoring, introduction of excess air downstream of the flame for gas temperature adjustment, bypass combustion gas venting, overpressure relief, and instrumentation access. The burner assembly is mounted to one end port. The opposite end port connects to the pipe train, which channels combustion gas from the firebox to the expansion chamber. The pipe train is assembled 10 in. OD components. These include two spacing spools, a high temperature butterfly valve (for firebox isolation), a short radius elbow which reduces overall system "straight-line" length to match available laboratory space, a heat exchanger which is used to fine tune gas stagnation temperature via cooling water throttling, and a 12 in. long "tailpipe" which contains small ports for optical, pressure, and temperature instrumentation.

The tailpipe section couples directly to the expansion chamber inlet port. The expansion chamber represents the primary experimental vessel for nozzle testing. The chamber is a stainless steel cylinder, 3 ft. in length by 2.5 ft. in diameter, whose multi-port design provides excellent optical and physical access to nozzle flow fields as well as for instrumentation integration. Interior flanges allow greater flexibility in experimental configurations. A transition piece provides for flow transition (circular to rectangular) to the straight walled nozzles.

Several other pieces of hardware comprise the CFS downstream of the expansion chamber. These pieces include a water-cooled heat exchanger which represents the final gas cooling device, a manual gate valve which is used to adjust the pressure in the expansion chamber, an electro-pneumatic valve which is used for blowdown initiation, and a cold trap which removes excess water from the gas stream. The exhaust gas is then directed to a pumping system or a blowdown tank. The pumping system is comprised of two Kinney KMBD 2700 units operating in parallel. Each system is a combination of two positive displacement pumps; a high vacuum mechanical booster pump and an oil-sealed rotary piston backing pump. This combination provides a pumping rate of 5000 cfm at pressures between 0.1 and 30 torr and 1700 cfm at pressures between 30 and 760 torr. The blowdown tank has an internal volume of approximately 800 ft³. The tank is employed during quasi-steady state operation where the pumps are inadequate to handle the generated flows.

Combustive Flow System Nozzle

As designed, the expansion chamber may be used in conjunction with many nozzle configurations. Initial comparison of CFD predictions was accomplished using a straight-walled, rectangular cross-section converging-diverging nozzle, illustrated in Figure 6. The nozzle has a 15:1 aspect ratio at the throat, thus simulating a two-dimensional planar flow. As depicted in the exploded view, the twenty-seven sampling ports are located in the nozzle upper

surface, and the sidewalls are removable to accommodate several experimental configurations. The throat height of 0.480 cm and divergence half-angle of 1.227° was influenced by the need to integrate experimental instrumentation and by the capacity of the pumping system. Nozzle stagnation pressures were monitored along the length of the nozzle with silicon diaphragm, Endevco fast-response piezoresistive transducers. Such transducers facilitate pressure measurements with a frequency of over one megahertz, and the small size (3.8 mm face diameter and 1.6 mm sampling port diameter) ensure minimal boundary layer interference. Output from the transducers were processed with a Measurements Group Model 2310 strain gage conditioner and amplifier, which provided a proportional output voltage for recording using a PC-based data acquisition system. Geometry of the nozzle may be modified for varying throat height and divergence angles, and the positioning of sampling ports allows for a variety of testing configurations.

Operation, Control and Measurement

The CFS provides continuous operation at ambient pressure conditions. Control is accomplished by altering the fuel/air ratio, adjusting the percentage of excess air introduced into the flow field downstream of the flame, and regulating temperature by means of the primary heat exchanger. A series of valves and capacitance manometers are used to monitor combustion constituents and provide precise control of the burner.

Measurement of experimental parameters are made throughout the flow field, providing data necessary to fine tune combustion and system operation. Thermocouples are located in the tailpipe, capacitance manometers and piezoresistive transducers measure pressures along the system flow path, and a combustion product analyzer is mounted in the firebox. Pressure and temperature data were gathered by an acquisition system connected to the thermocouples and transducers, as presented in Figures 8 and 9. This system provided real time analyses of system performance, the results of

which could then be applied to data yielded by other instrumentation. Additional diagnostic techniques were used in the comparison of nozzle performance to CFD predictions. Pitot and static probes were installed in one of the sidewalls to ascertain boundary layer and shock conditions, and a schlieren flow visualization system was used to provide qualitative flow information.

The pitot tube and static probe measurements for this study were performed with a circular, 0.105 cm OD, stainless steel tube. The sampling tubes were sealed inside of a 0.315 cm OD high-pressure (thick wall) tubing, which provided structural support and minimized vibration. The sampling tube length was kept short to minimize gas volume and decrease response time. The tubes were connected via a small volume coupling to a fast-response piezoresistive transducer of the type discussed previously. Pitot and static probe data were obtained using the aforementioned strain gage conditioner arrangement. The probes were designed to scan vertically at various positions downstream of the throat. A precision resistor was used to establish the position of the probe. Data from these probes were recorded using an XY plotter and were then correlated to nozzle transducer information to yield local Mach numbers and boundary layer information.

A schlieren system comprised of two 10-cm diameter, f/3.6 lenses, knife edge, light source, and Cohu CCD camera was used to provide real time imaging during flow surveys. Output from the camera was fed through a video recording and frame-grabber system for storage and playback. These images were used in conjunction with transducer data to provide further insight into system behavior.

Computational Fluid Dynamics Code Comparison

FLUENT, a product of Fluent, Inc., was used to provide CFD simulations of measured flow field properties. This code is capable of analyzing steady or unsteady two-dimensional, axi-symmetric, and three dimensional systems with complex geometries. It also allows for the

study of incompressible and compressible flows, and will model subsonic through supersonic regimes. Three turbulence models provide for both laminar and turbulent flow. Packages for particle tracking, reactive flows, and multiple boundary conditions are also incorporated into the LANL setup.

Experimental Results and Discussion

Tests were performed at various temperatures to compare measured values and CFD predictions over a broad range of conditions. When the measured values are compared to calculations using a one-dimensional analysis, depicted in Figure 9, it is evident that disagreement occurs with progression downstream. Figure 10 illustrates the fact that data obtained with the FLUENT code does not display these discrepancies. These graphs are typical of experiments performed at different temperatures and flow conditions. Further investigation of other nozzle parameters such as static pressure, as presented in Figures 10 and 11, provide additional justification for the benchmarking capability of the Combustive Flow System. Measured values for Mach number also corresponded to FLUENT calculations. Figure 12 provides a comparison of one-dimensional analysis to pressure ratio calculations of Mach number from the experimental data and FLUENT calculations.

Summary

A combustion driven, supersonic flow system has been constructed to facilitate the comparison of experimentally determined values and the establishment of a data base to benchmark CFD codes. Preliminary tests have served to verify the idea that complete kinetics model verification and subsequent component design and performance evaluation requires experimental measurements in an environment emulating that for which the CFD was designed. Further refinement of experimental procedures and reduction of data will furnish a more detailed representation of system capabilities. Additional diagnostic techniques may then be used to

establish a more qualitative analysis of the predictive capabilities of CFD packages.

Acknowledgement

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*Combustion-Driven Flow System
Burner and Methane / Air Supply System*

Fig. 3

Combustion-Driven Flow System Ventilation and Pressure Relief Piping

Fig. 4

Pumping Station for Combustion-Driven Flow System

Fig. 5

Straight Wall Nozzle for CDFS Experiments Showing Pressure Transducer Location

Fig. 6

Transducer number	X - X throat (cm)
1	-2.69
2	4.29
3	9.98
4	15.67
5	21.41
6	27.76
7	33.48
8	39.19
9	46.97

Characteristics

- All stainless steel construction
- Can vary separation and divergence angle
- Current design: $\theta_w = 1.231^\circ$
- $A_e / A_t = 5.3$
- Overall length = 20.25"

Fig. 7

Nozzle Pressure Data Acquisition System

Mach Number vs $X-X_{throat}$

Mach Number vs $X-X_{throat}$

Fig 10

Static (Wall) Pressure vs $X-X_{\text{throat}}$

Fig 1.2

Fig 1.1