

Fuel-Flexible Gas Turbine Combustor Flametube Facility

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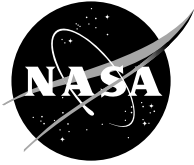
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Summary

Facility modifications have been completed to an existing combustor flametube facility to enable testing with gaseous hydrogen propellants at the NASA Glenn Research Center. The purpose of the facility is to test a variety of fuel nozzle and flameholder hardware configurations for use in aircraft combustors. Facility capabilities have been expanded to include testing with gaseous hydrogen, along with the existing hydrocarbon-based jet fuel. Modifications have also been made to the facility air supply to provide heated air up to 350 psig, 1100 °F, and 3.0 lb_m/s. The facility can accommodate a wide variety of flametube and fuel nozzle configurations. Emissions and performance data are obtained via a variety of gas sample probe configurations and emissions measurement equipment.

Introduction

A continuing challenge for the development of advanced jet engines is meeting stringent global emission requirements. The tightening of allowable emissions levels has increased the challenge to design fuel injectors that can promote efficient combustion while reducing harmful emissions. The two primary emissions of concern when developing gas turbine combustion systems are nitrogen oxide (NO_x) and carbon dioxide (CO₂). A variety of fuel injection schemes have been developed over the years to address the need for reduced emissions. The most common method to test new fuel injection concepts is in a flametube facility. This type of facility provides conditions that simulate those a gas turbine combustor would encounter during normal operation, including long-duration tests in excess of 8 h. This mode of testing provides means to isolate the combustion process and quantify the performance of individual fuel nozzle designs. The relative simplicity of this type of testing can provide an efficient means to evaluate a wide variety of configurations.

A significant amount of combustion research has been conducted at NASA Glenn Research Center under a variety of projects including the Advanced Subsonic Transport (AST), the High-Speed Research (HSR), the Ultra-Efficient Engine Technology (UEET), and Propulsion and Power (P&P). Research under these projects, with the support of Glenn facilities, has led to significant breakthroughs for the reduction of engine emissions, particularly NO_x. However, despite the tremendous advances made with reducing emissions from hydrocarbon-based jet fuels, using alternate fuels can further reduce emissions. One of the most highly regarded fuels is hydrogen, which is used extensively in rocket engines.

The use of hydrogen as a fuel for gas turbine engines provides several areas of potential improvement over current state-of-the-art hydrocarbon-based fuel systems. One significant area is the elimination of

CO₂ emissions. Also, with hydrogen one does not have to worry about fuel coking in the injector or particulate emissions. Combustor lengths can be very short due to the increased kinetics of hydrogen as compared with hydrocarbon-based jet fuel. However, even with these advantages, NO_x emissions are still a significant concern when using hydrogen. Despite some drawbacks, the potential improvements made possible with hydrogen have renewed interest in its use for gas turbine applications. This led to NASA's development of the Zero CO₂ Emission Technology (ZCET) and Revolutionary Aeropropulsion Concepts (RAC) subprojects under the P&P project. The goal of these projects is to study fuel injection concepts for aircraft gas turbine engines that meet conventional gas turbine performance levels and provide low levels of NO_x emissions.

Over the years, test cell 23 in the Research Combustion Laboratory (RCL-23) at Glenn has been used for a variety of experiments related to the development of combustors including rich-burn, catalytic combustion, rich-burn quick-quench lean-burn, and lean premixed prevaporized combustors. A facility that has the flexibility to efficiently test a variety of fuel nozzle configurations is necessary to meet the changing need in the development of gas turbine combustors. With that in mind, the capabilities of RCL-23 have been expanded to provide increased air pressure capacity and the option of using gaseous hydrogen fuel.

Facility Overview

Test cell RCL-23 is just one of several combustor tests facilities at Glenn (ref. 1). In combination, these facilities can accommodate a wide range of test conditions and hardware configurations. RCL-23 is located in the Research Combustion Laboratory complex of Glenn, which consists of a number of small test facilities designed for combustion research, materials evaluation, and fuel cell development. Figure 1 shows an external view of RCL-23.

The RCL-23 facility consists of a control room and test cell, separated by a reinforced concrete wall, and some additional space in an adjoining test cell. The main research test cell is approximately 24.6 by 17.5 ft. The control room houses all of the electrical and electronic components for facility control and operation. All data acquisitions systems are also located inside the control room. A remotely operated gas bench for measuring emissions during testing is located in an adjoining test cell.



Figure 1.—External view of Research Combustion Laboratory Cell 23 (RCL-23).

Ambient-temperature research air is piped to the cell from a central system at the laboratory. The research air is then heated with a shell and tube heat exchanger driven by a separate facility preheat combustor. Propellant storage is located remote from the facility behind earthen mounds. The facility currently has the capability to run with liquid hydrocarbon-based jet fuels and trailer-supplied gaseous hydrogen.

Mechanical Systems

The table below summarizes the current facility capabilities of RCL-23. A detailed description of the individual systems follows.

Maximum research airflow, lb _m /s	3.0
Maximum hydrogen flow rate, lb _m /s	0.05
Maximum jet fuel flow rate, lb _m /s	0.62
Maximum nonvitiated research air temperature, °F.....	1100
Maximum research air pressure, psia	350
Maximum combustion temperature, °F	3200

Air System

Research airflow rates up to 3 lb_m/s are possible with the 450-psig supply system over a range of inlet temperatures. Air is piped to the facility from the central control system at Glenn. The central control system uses a series of compressors to supply the entire Glenn facility with the compressed research air. The air is preconditioned by using air dehydrators to keep the dew point between -15 and -144 °F. The air is also kept free of any contaminants such as oil and is filtered for particulates at the 50 µm level (ref. 1).

Once at the facility, the air is split to supply both the research combustor and facility preheat combustor. Research air is provided to the facility through 3.0-in.-diameter feed lines. Flow control and flow measurement occur upstream of the heat exchanger inlet. Flow measurement is accomplished with multiple, calibrated subsonic venturis, depending upon inlet pressure. The research air is then fed to a two-loop shell and tube heat exchanger where it is warmed to the desired inlet temperature by the exhaust gases from the facility combustor. Research air then exits the heat exchanger where it is supplied to the test hardware, while the spent facility preheat combustor gases are exhausted out of the facility.

Fuel Systems

The facility is capable of testing with both gaseous hydrogen and liquid hydrocarbon-based jet fuels. It is anticipated that the gaseous hydrogen system could also be modified to accommodate methane, propane, and natural gas if the needs arise.

The gaseous hydrogen is supplied from a 70 000 stdft³ tube trailer at flow rates up to 0.05 lb_m/s. Supply pressure can be regulated up to the trailer maximum supply of 2400 psig. Flow control is accomplished with a pneumatic globe valve. Both a calibrated subsonic venturi and a coriolis-type mass flowmeter provide flow measurement. Because of safety requirements, all connections in the hydrogen system within 50 ft of an ignition source are enclosed in purge boxes. Within these boxes a small amount of nitrogen flows across the components and is vented past a hydrogen detector. Should any leak occur, it can be vented safely and the detectors will alert the operators to any potential hazards.

The maximum total liquid hydrocarbon-based jet fuel that can be supplied to the research hardware is 0.62 lb_m/s at 480 psig. Fuel is stored in a 600-gal tank and supplied to the test rig via a pumped feed system. Valves provide flow control, and measurement is accomplished with a coriolis-type mass flowmeter. Maximum jet fuel flow rate for the facility combustor is 0.62 lb_m/s, and, similar to the

research system, valves provide flow control, and measurement is accomplished with a coriolis-type mass flowmeter.

Heat Exchanger System

Nonvitiated, hot research air is supplied through a two-loop shell and tube heat exchanger. As shown in figure 2, the unit is insulated on the exterior to reduce heat loss. The hot supply gases flow through 379 Hastelloy (Haynes International, Inc., Kokomo, Indiana) tubes having 0.75-in. outer diameters. The vitiated air for the heat exchanger is supplied from the facility preheat combustor (fig. 3), which operates with hydrocarbon-based jet fuel and air. Fuel is pump fed from the same 600-gal fuel tank also used by the research combustor. Inlet temperatures to the heat exchanger are limited to 1300 °F at 90 psia with a maximum airflow rate of 4.0 lb_m/s. Maximum nonvitiated facility air temperature is 1100 °F at 1.0 lb_m/s. The performance envelope for the heat exchanger is shown graphically in figure 4.

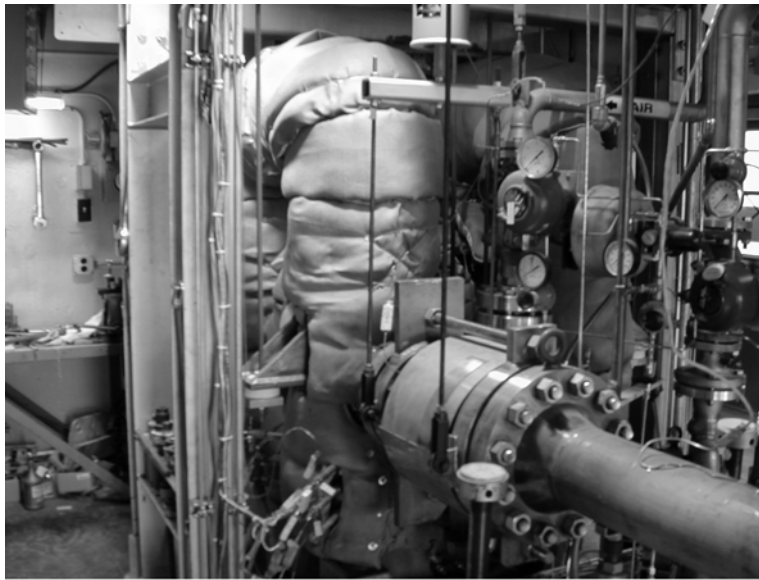


Figure 2.—RCL-23 shell and tube heat exchanger.

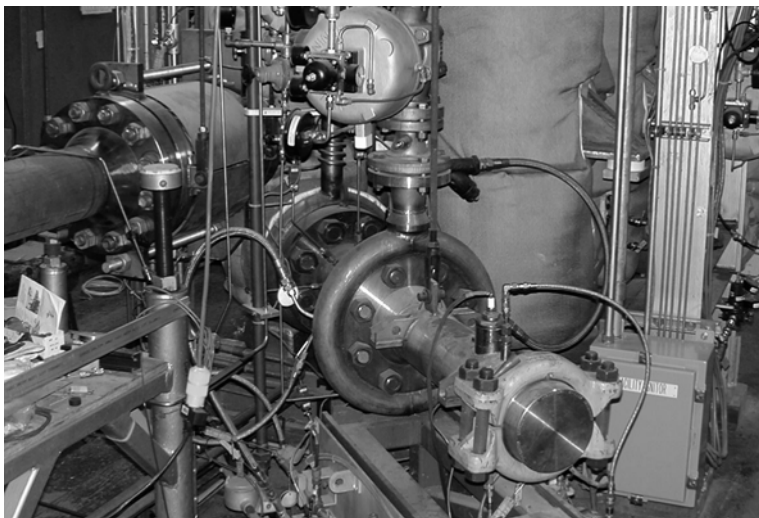


Figure 3.—RCL-23 facility combustor.

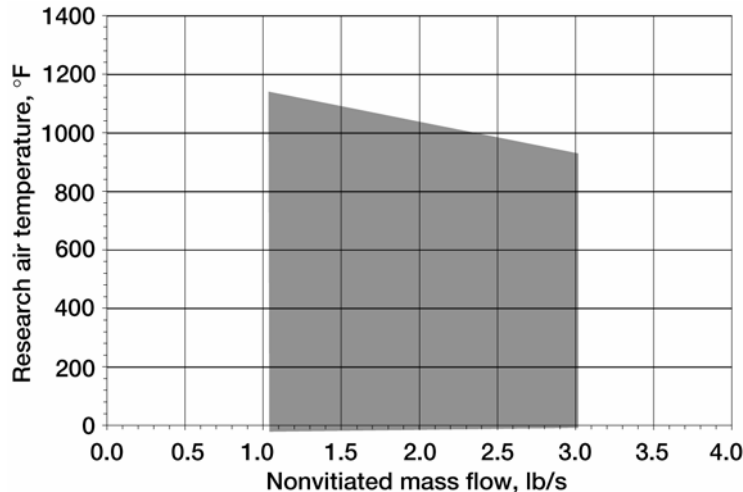


Figure 4.—RCL-23 heat exchanger operating envelope. Research inlet air temperature as function of nonvitiated airflow rate.

Purge and Cooling Systems

Nitrogen is utilized for the main facility and research hardware purge system. The nitrogen is also used to sweep any potential hydrogen leaks past detectors in all test cell electrical boxes. The gas is supplied from a centralized 16 000-stdft³ accumulator maintained at 2250 psig. Depending upon the system, individual regulators are used to set purge pressures. Nitrogen is also used for fuel system valve actuation.

Water is used extensively in the facility for quenching the exhaust gases and cooling the hardware. System input is a domestic water source and is not deionized. Maximum facility flow rates are 118 gal/min at 115 psig utilizing the facility main water pump. The cooling system is primarily used to quench the hot gases downstream of the research and facility combustor sections before entering their respective exhaust stacks and to cool the research combustor pressure control valve. The system also cools the research combustor housings, gas sample probes, and thermocouple housings located in the combustor test section.

Research Systems

RCL-23 is a highly flexible test facility that can perform a variety of flametube combustion experiments. The main facility research section consists of a variable length inlet pipe, fuel injector housing, combustor housing, an ignition system, a set of gas sample probes, and the gas analysis system. Figure 5 shows a cross section of the facility research section with three gas sample probes installed.

Facility Research Section

The RCL-23 facility research section (fig. 6) has a total length of 100 in., running from the outlet of the heat exchanger to the water-cooled backpressure valve housing. The exit of the heat exchanger has a short baffle section to allow for thermal growth during test runs. The research hardware can fit anywhere within the 100-in. section, but generally the combustor is located just upstream of the water-cooled backpressure valve housing. The research hardware inlet interface flanges can be either 6-in., 900-lb flanges or 8-in., 900-lb flanges. The test cell can also accommodate round or square hardware configurations. The combustion section and inlet pipes can be either actively cooled with water or passively cooled with internal ceramic liners, or both. The combustion temperature in the research housing is limited to 3200 °F, which is the limit for survivability of the ceramic liners.

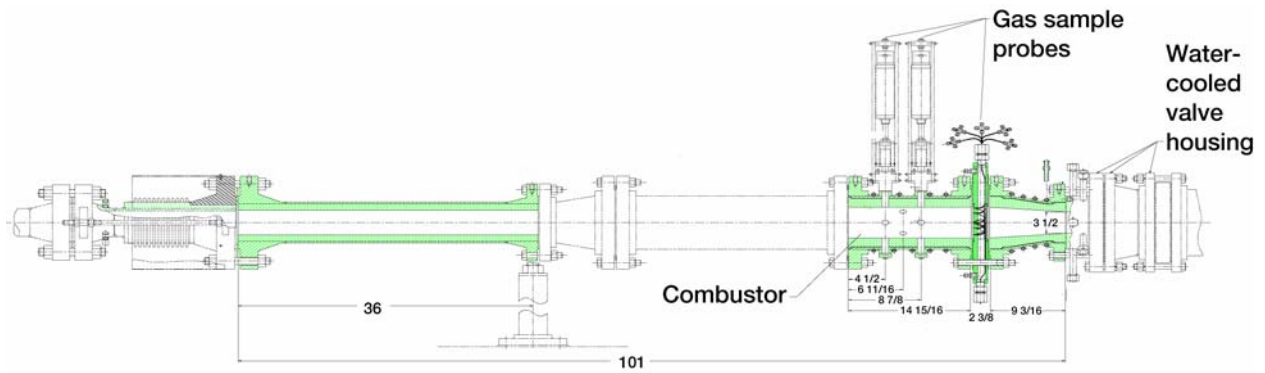


Figure 5.—Cross section of RCL-23 facility research section; dimensions are in inches.

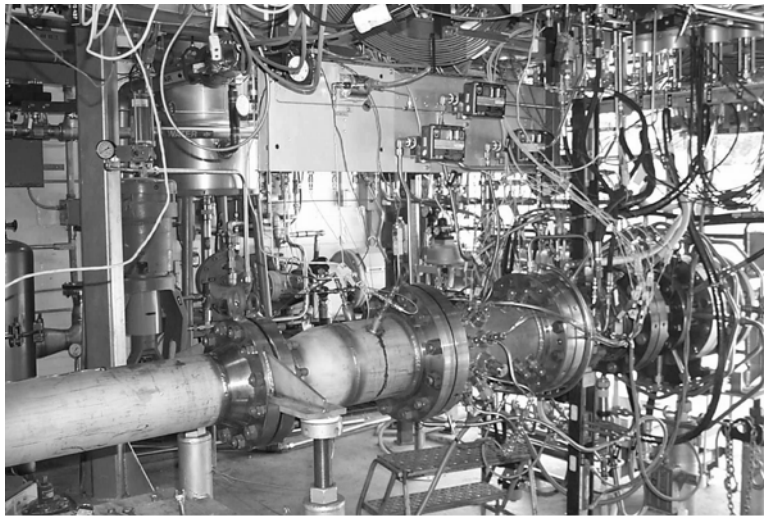


Figure 6.—Typical flametube installation for RCL-23.

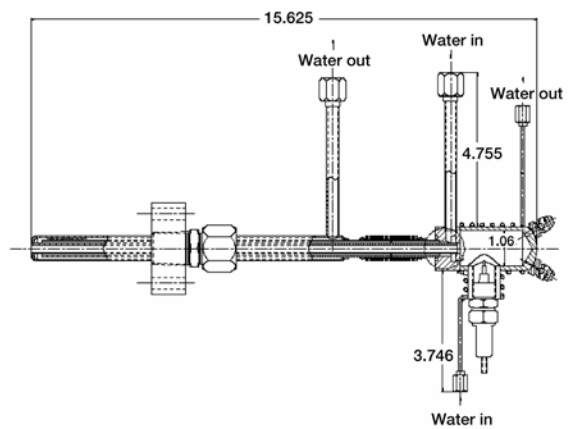
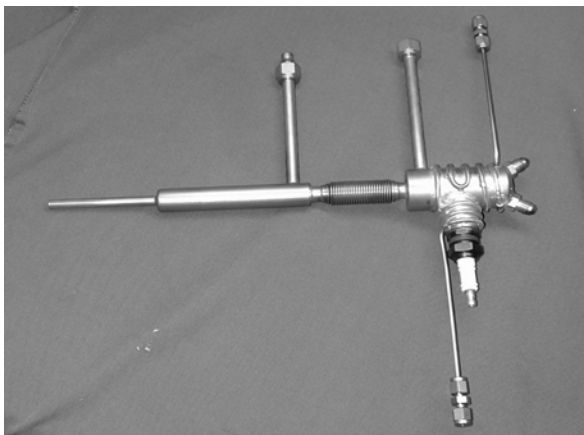


Figure 7.—Hydrogen-air torch igniter; dimensions are in inches.

Ignition system

Two common ignition systems are available, a gaseous hydrogen-air torch and electronic spark igniter. The gaseous hydrogen-air torch mounts into the side of the combustor housing. The torch, shown in figure 7, has a combustion cavity with a spark plug ignition source and a 12.8-in. exhaust tube. Air is supplied from the main 450-psig system and gaseous hydrogen from the main propellant systems.

Nominal flow rates are 0.0505 and 0.0042 lb_m/s for air and gaseous hydrogen, respectively, at a nominal combustion equivalence ratio of 2.8. The torch system is water cooled for 6.5 in. downstream of the combustion cavity, but the remaining 6.3 in. is left uncooled to retain an exhaust temperature of 2200 °F.

An alternate ignition system is an electronic jet engine igniter that mounts directly into the combustor housing. This spark igniter provides 250 W of energy at 60 Hz.

Gas Sample Probes

The gas sample acquisition system consists of the gas sample probe itself, heated lines to transport the sample, and an actuation method for inserting the probes into the combustor. A new water-cooled gas sample probe has been developed for use in the hydrogen testing (fig. 8). The unique feature is a thermocouple attached to the probe that is inserted with the probe into the hot gas stream. This allows for temperature measurements to be obtained at approximately the same location and time as the gas sample is drawn. The probes will draw 10 to 15 liter/min (standard) of sample from the combustion zone into the heated trace lines and on to the gas analysis bench. The heated trace lines are kept at 300 °F to prevent condensation of water in the sample.

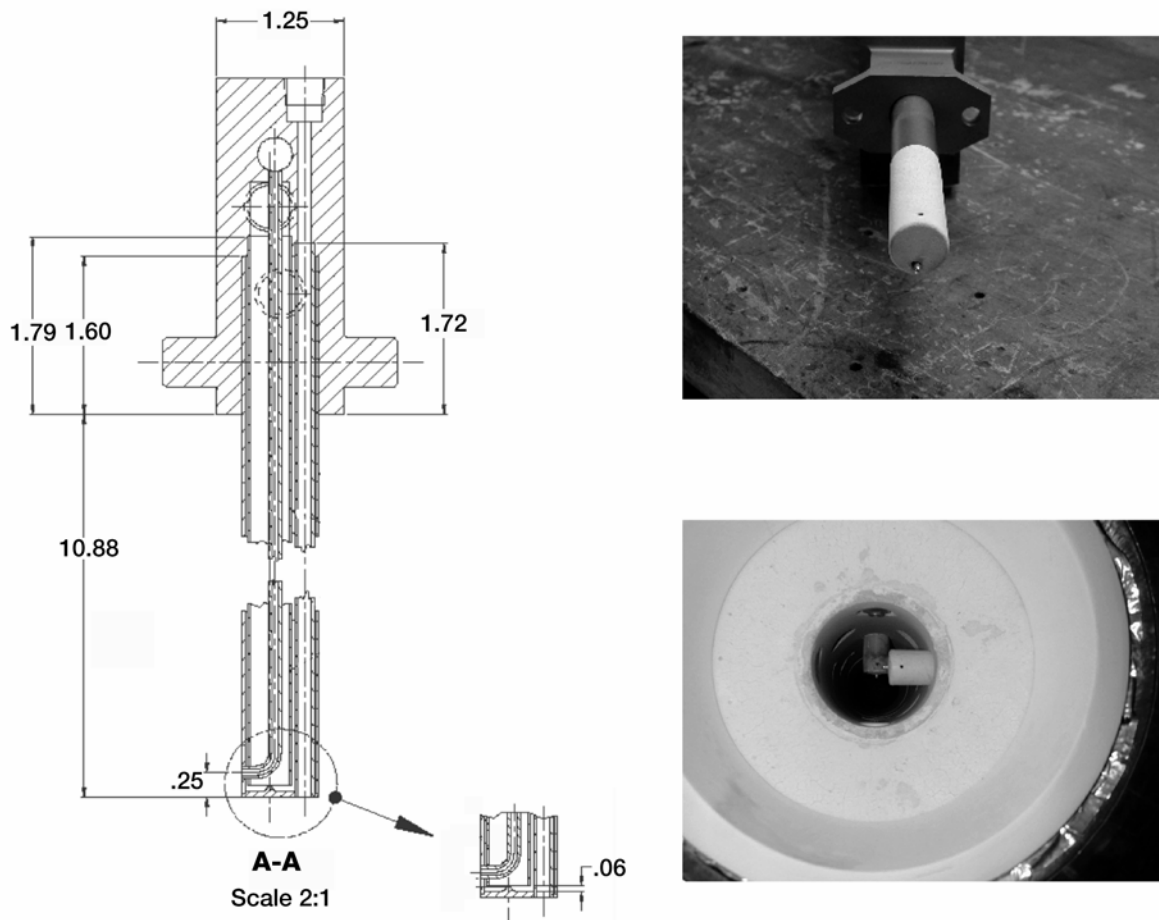


Figure 8.—RCL-23 gas sample probe configuration with imbedded thermocouple; dimensions are in inches.

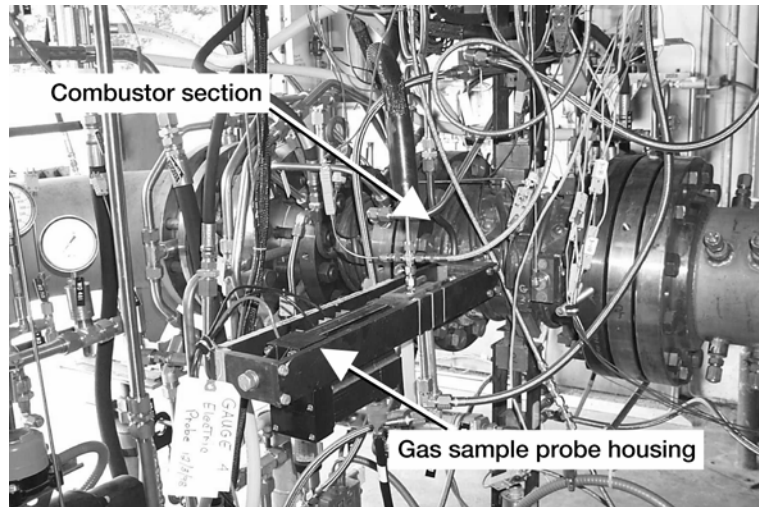


Figure 9.—Typical gas sample probe installation.

Two methods, pneumatic and electromechanical, are available for inserting the gas sample probes into the combustor section. Figure 9 shows a gas sample actuation assembly mounted to a research combustor. Pneumatic actuation of the probes provides for a single radial point location within the flow stream, most commonly the centerline. This process will allow for the probes to be in the flow stream or fully recessed outside of the combustion zone. Electromechanical actuation allows for multipoint data at the given axial location. The probe can be programmed to stop at any radial location via a control unit, which then allows data to be gathered at multiple radial locations.

Gas Analysis System

The gas analysis system, or more commonly referred to as the gas bench, is the primary source of data collection for both emissions and performance results. A variety of units are available for measurement of the fuel nozzle emissions. The most common units measure carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO and NO_x), oxygen (O₂), unburnt hydrocarbons (UHC), and unburnt hydrogen. Each measurement is accomplished with an individual module. Other modules can be easily added to the system.

Electronic Systems

A significant level of effort has been performed to modernize the control systems and data acquisition systems for RCL-23. The result is a highly flexible control architecture that allows for quick changes of research and operational configurations. The facility has moved away from a labor-intensive hardware interface and transitioned to a software-configured interface system.

Facility Control

A complete modernization of the facility control architecture has recently been completed. The facility and gas bench operations have moved away from a push button control system to a system driven from graphical operator interface (GOI) screens and software programming. Facility condition monitoring and data acquisition are performed by a Glenn-developed ESCORT data analysis system (described in the forthcoming Data Analysis section).

A programmable logic controller (PLC) is used for controlling discrete input and output facility functions during test sequences. Individual system process controllers with pressure, mass flow, or temperature feedback loops control the operational pressures, airflows, and the heating and cooling processes, respectively.

Remote drop utilization allows for a compartmentalized layout of the facility for future test modifications with minimal field wiring. The system presently houses five drops with 804 channels of input and output capability; 275 channels are presently utilized. The annunciator system contains 78 channels programmed via a high-speed industrial serial buss interface through the PLC and GOI software. A representation of the hardware annunciator system is mirrored on the GOI screens. When a window is activated to indicate an alarm or shutdown condition, the operator can select the active window via the GOI annunciator representation, and the system alarm or shutdown parameter of concern is brought to the front for quick identification.

One facility PLC with a network interface module controls all facility and test hardware discrete systems. This PLC communicates with a logic programming personal computer (PC) and the GOI workstations via Ethernet protocol. All PCs, the PLC, and the ESCORT CPU are networked together via an auto sensing 10/100 Mbps Ethernet switch to form an isolated local area network (LAN). The facility GOI system resides on three operator workstation PCs with touch screen monitors. One PC is configured as a network server and performs the functions of domain controller, software development station, and historical data logger. The interface between ESCORT and the PLC is configured to specifically scan a range of registers and provide data transfer between the two systems. This allows for real-time updates of the subsystem displays, which are operational renditions of the facility design process and instrumentation diagrams. This display capability places the engineering unit parameter value next to the indicated instrumentation device on the GOI display. This numeric representation of the facility process to a visual component is an operational improvement over the former ESCORT text displays.

All facility operation GOI screens display the system status bar at the top of their respective page. This status bar indicates the GOI software version number, communication link health, permissive and/or shutdown status, and hydrogen detector output and/or health. When a permissive is lost and a shutdown occurs, the respective indicator will be activated, the annunciator reference number will display, and a pop-up window will indicate which device(s) initiated the shutdown and the status of the field devices affected by this shutdown. The hydrogen detectors provide a graphical indication of the reading relative to the alarm condition that is easy for the operators to quickly interpret.

The facility GOI screen architecture comprises four system categories with two to four subsystem screens in each category supporting the present test requirements. These screens operate the primary functions of the facility and will not change without major modification to facility hardware or control components. Gas bench control and display screens are modified as per research configuration requirements. Research data acquisition, sampled channel display, and calculated word display or graphics are presently handled exclusively through ESCORT. The history trend graphing and data capture capabilities of the GOI system are presently utilized for operational parameters only. This data-logging tool is an easily configured resource to assist with tuning system control loops, troubleshooting parameter faults, and monitoring facility health while operating.

Instrumentation

RCL-23 can support a variety of instrumentation requirements. A total of 199 channels are available for data acquisition. The most common types of measurement obtained are pressure, temperature, volume flow, mass flow, and position. Pressure measurements are obtained using a variety of strain-gauge- and silicon-diaphragm-type pressure transducers. Temperature measurements are available using type K or R thermocouples. Volumetric flow is achieved using turbine- and venturi-type flowmeters. Fuel system mass flow measurement is achieved using coriolis affect instrumentation to measure fluid mass directly instead of inferring mass from a volumetric-temperature measurement. Air system mass flow is derived

from pressure and temperature readings across calibrated venturies utilizing the FORTRAN calculation capabilities of ESCORT. Electric gas sample probe positional readings are input into the ESCORT data acquisition system utilizing digital-to-analog converters on the probe system indexers. Barometric pressure referencing to assigned channels of the facility data acquisition system is achieved with a high-accuracy instrument using a resonating silicon sensor to measure from 23 to 34 in. Hg absolute, with a scaled 0 to 10 V dc output to the data acquisition system.

Data Acquisition

Data acquisition is accomplished by a locally housed Glenn-developed ESCORT system, which samples at a rate of 1 Hz and converts millivolt signals to engineering units. The system can sample continuously or be triggered for individual data points at specific conditions. The data system allows for real-time monitoring of all facility and research data. Online calculations and graphics capability are also available for real-time data evaluation. Data acquisition for the test cell is provided by a computer-controlled NEFF System 470 (NEFF Instrument Corporation, Monrovia, California). The NEFF programmable gain amplifier receives the multiplexed analog input signals via the test facility instrument interconnect and provides 12 programmable full-scale increments ranging from 5, 10, and 20 mV up to 1024 mV. Each of the facility's 199 total channels can be individually programmed for the best accuracy in the expected range. The sample-hold amplifier and 16-bit analog-to-digital converter process the analog voltage to digital words. The facility includes four ESCORT monitor displays and a laser printer for online data interface. The page displays and research calculation FORTRAN code are configured for each test application. Postprocessing of test results is specified by the research engineer or scientist and is custom configurable for each test application.

Concluding Remarks

Test cell 23 of the Research Combustion Laboratory (RCL-23) has been upgraded with the addition of gaseous hydrogen as a working propellant and the addition of a 450-psig air supply system. Test flexibility has also been further enhanced by upgrades to the facility control systems. The facility is able to test with gaseous hydrogen flow rates up to 0.05 lb_m/s and liquid hydrocarbon-based jet fuel flow rates up to 0.62 lb_m/s. Research airflow rates up to 3 lb_m/s are possible with the 450-psig supply system over a range of inlet temperatures. Nonvitiated heated air is supplied from a shell and tube heat exchanger. Maximum nonvitiated facility air temperature is 1100 °F at 1.0 lb_m/s. Research section exhaust temperatures are limited to 3200 °F based upon material and cooling capacity limits.

A variety of support systems are available depending upon the research hardware configuration. Test section ignition can be provided via either a hydrogen-air torch system or an electronic spark system. Emissions measurements are obtained with either pneumatically or electromechanically actuated gas sample probes. The electromechanical system allows for radial measurements at a user-specified axial location for measurement of emissions profiles. Gas analysis data can be obtained for a variety of substances such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO and NO_x), oxygen (O₂), unburnt hydrocarbons (UHC), and unburnt hydrogen.

Facility control is accomplished with a programmable logic control system. Facility operations have been upgraded to a system based on graphical user interface control screens. A data system is available for the acquisition of engineering units and subsequent execution of performance calculations in real time. The upgrades have made RCL-23 a highly flexible facility for research into low-emissions gas turbine combustor concepts. The flametube configuration inherently allows for a variety of fuel nozzle configurations to be tested in a cost-effective manner. RCL-23 is poised to be a leading facility for the development of modern low-emissions fuel nozzles for use with liquid hydrocarbon-based jet fuels and gaseous alternative fuels.

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