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Evaluation of the Transient Operation of Advanced Gas Turbine Combustors

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A unique test capability has been defined and used to evaluate the transient response of advanced gas turbine combustors. This facility offers the opportunity to achieve predefined time variations of the air and fuel flow rates and air temperature delivered to a combustor model. This capability can be used for model scales ranging from multinozzle combustor sectors to smaller setups focusing on one component or process. A dedicated control computer aids in establishing time profiles for the input parameters and automatically executing the transient test. Among its applications, the facility has been used to study the occurrence of in-nozzle fuel vaporization during Bodie cycles and to assess the tolerance of a fuel-staged combustor to rapid fuel redistribution.

Introduction

THE aircraft gas turbine engine continuously undergoes operational transients. From the moment the engine is ignited, and through taxi, takeoff, climb, cruise, descent, and landing of the aircraft, the engine is requested to vary its thrust level. Often these variations are accomplished over a long time period so that the rate-of-change is small and the engine is essentially operating in a "quasisteady process." In such instances, both the engine response and the aircraft maneuvers are smooth; this is a goal of commercial aircraft operation.

In other instances, the requested variations are rapid rates-of-change of power, altitude, and attitude. These conditions alone may result in transient inputs to the combustor, or they may cause other engine components to enter unsteady operation such as compressor stall. Correspondingly, the conditions approaching and within the combustor are truly transient. While such maneuvers can be easily imagined for high-performance military aircraft, they can also be encountered by commercial aircraft during emergency avoidance procedures. These engine transients are not a series of steady states, but a combination of coupled, unsteady processes. In the combustor, processes including fuel delivery and atomization, air flowfield structuring, fuel-air mixing, and combustion interact to determine the instantaneous performance and emissions of the burner.

Traditionally, the performance of gas turbine combustor systems and components is evaluated only at steady-state conditions. That is, design point combinations of the burner air and fuel flow rate, air temperature, and pressure are set, and combustor exit temperature and emissions profiles are measured. Even the stability evaluation of lean blowout is determined under quasisteady conditions, with slow variations of the fuel flow rate for fixed levels of airflow rate and temperature. The operability of the combustor, i.e., the tolerance of the combustor performance and stability to rapid transients in burner conditions, is evaluated only after completing the development of the total engine. At this point in the development cycle it is difficult and costly to accomplish major changes that overcome deficiencies. Sometimes the only practical strategy is to contract the operating envelope of the system with an obvious loss in capability.

This situation is worse for advanced gas turbine combustors in which processes are highly coupled. For example, acceptable performance of aerating fuel nozzles relies upon maintaining a balance of air and fuel momenta to achieve desirable atomization and distribution characteristics. Transient flows may disrupt this balance and dramatically alter the resulting fuel-air ratio distribution within the burner. Furthermore, combustor systems being considered to achieve low emissions of NO_x may employ fuel or air staging. The transition through the staging points during engine acceleration or deceleration must be studied to assure that burner operability is preserved.

This unique test capability is being used to evaluate the operability of gas turbine combustors during transient events. The facility offers the opportunity to achieve controlled time variations of combustor air and fuel flow rates, and air temperature delivered to a combustor model. This article will describe the facility operation and illustrate its use in evaluating operability issues encountered with advanced gas turbine combustors.

Transient Combustor Facility

Transient Operation Goals and Flow Rates

The Transient Combustor Facility was conceived to evaluate the nonsteady-state response of combusting or noncombusting systems when subjected to prescribed, controlled variations of the input parameters. In particular, it was sought to control the total air and fuel flow rates and the air temperature delivered to an experimental model. This capability was desired for model scales ranging from a multinozzle sector of a gas turbine combustor to an experimental setup focusing on one component or process. In the latter category, the model might contain a single aerating fuel nozzle or a rearward-facing step to study the influences of transient flows on atomization or stabilization, respectively.

The facility and its control system were specified to achieve flow transients as depicted in Fig. 1. Two types of time variation were sought: monotonic and oscillatory.

The monotonic variations, represented as combinations of 10-ms duration linear segments, characterize events occurring over a nominal 0.5-s period or longer. While the variation during each segment is monotonic (e.g., an increase or decrease in a flow rate), the combination of them need not be monotonic, but could trace increasing and decreasing flows. As indicated below, the control system updates its set-point every 10 ms. Hence, variations on this time scale are possible for this "slow" mode. However, most large-scale engine tran-

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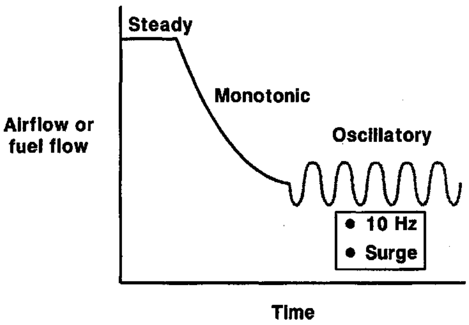


Fig. 1 Target transient profile.

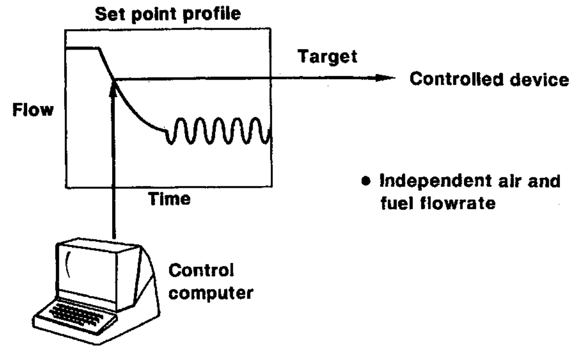


Fig. 2 Transient control logic.

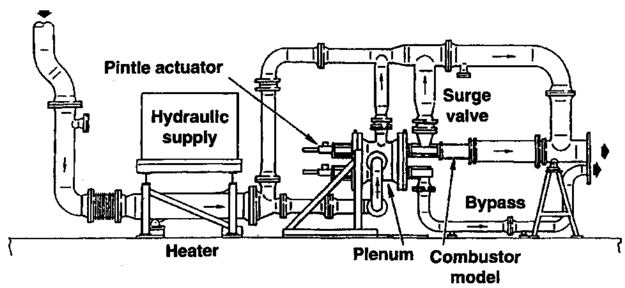


Fig. 3 Transient airflow system.

sients follow specific time profiles over their duration. The 10-ms period permits 50 updates of the flow set-point during a 0.5-s event, enabling a controlled transition during it. Typically, set-point changes by a factor of 2 are accomplished during a 1-s period, which precisely track a desired time profile. The air and fuel flow rates and air temperature can be controlled to follow such variations.

Oscillatory variations can be achieved for air and fuel flow rates, but not for air temperature. The variation is prescribed by defining the amplitude, frequency, and phase-lag associated with a cosine wave form, and a single start and stop time combination of the oscillation. If it is desired to synchronize air and fuel flow rate variations, then the maximum air or fuel flow oscillation is 10 Hz. If synchronization is not required (e.g., airflow oscillation with constant fuel flow rate), airflow oscillation frequencies up to 60 Hz can be accomplished although at the expense of an approximately 50% attenuation of the amplitude. Typically, the amplitude of the oscillations can range up to 25% of the mean. For operation up to a frequency of 10 Hz, no significant phase-lag or amplitude attenuation is experienced.

The two types of flow variations can be accomplished either alone or in combination. Figure 1 is an example of a combined variation that might simulate an engine deceleration leading to a stalled (i.e., oscillatory) airflow entering the burner. The monotonic variation mode can be used to produce ramps, steps, or nonsinusoidal variations. Alternatively, oscillatory variations of air and/or fuel flow rates can be requested for steady mean values.

The model scale and transient profile goals led to defining a test facility with the following flow capabilities:

1) Controlled airflow rates to a test model of up to 15 lbm/s for a 225-psia model pressure and down to 1 lbm/s for 20 psia.

2) Airflow heating to produce controlled temperatures ranging from 300° to 850°F at the test model.

3) Three independently controlled liquid fuel delivery systems with flow rate capability ranging from 30 to 300 lbm/hr for two systems, and a range of 60 to 2000 lbm/hr for the third system.

4) Steam heating of the fuel to produce a steady fuel temperature up to 300°F.

Transient Test Control System

A key element of the Transient Combustion Facility is the control system that guides the setup and execution of the transient test. The control strategy is based upon, firstly, establishing a profile set of the desired time variations of test model inputs, and secondly, stepping through this profile set in 10-ms increments to send new target signals to the hardware responsible for achieving the flows (depicted in Fig. 2). The control computer storage permits executing transient tests with a total duration of 30 s.

Five profiles constitute the set for a desired transient test, one each for airflow rate and temperature, and three for the fuel flow rates. As described above, the profiles for air or fuel flow rate can consist of combined monotonic and oscillatory transients. The monotonic portion of each profile is defined by up to 45 coordinate pairs of time and flow rate. The pairs do not have to be incremented by the 10-ms set-point update period; set-points are determined every 10 ms by linear interpolation between sequential coordinate pairs. The oscillatory portion of a profile is described by its amplitude and frequency. The monotonic and oscillatory portions are added to form the total profile for air or fuel flow rate. The air temperature profile can consist only of a monotonic profile.

A typical transient test consists of establishing a steady-state condition matching the initial conditions of the transient, followed by a computer-controlled stepping through the set-point profile set. Every 10 ms, new targets for airflow rate, fuel flow rate, and air temperature are established and sent to the control hardware for closed-loop control. As described below, the airflow rate control is achieved by using measured air pressure and temperature conditions to determine an appropriate flow area, and positioning a pintle in a venturi to achieve the area. Fuel flow rate control is achieved by actuating a valve until the metered flow rate equals the target. The air temperature control is achieved indirectly. The temperature profile is translated into a heater fuel flow rate profile using thermochemistry and heat loss considerations. The profile is shifted in time to account for the convection time delay from the heater to the test model. This two-step translation of the air temperature profile occurs automatically during a brief period once the transient test has been initiated.

Airflow Control System

An airflow system capable of delivering controlled ramp, oscillatory, or combined ramp-oscillatory transient airflow to a test model has been acquired. Consideration of the above system goals led to specifying a system with the following features as depicted in Figs. 3 and 4:

1) A propane-fired, vitiating air heater is used to achieve the desired test section inlet air temperature. Replenishment oxygen is added upstream of the heater to achieve an oxygen mole fraction of 21% in the gas delivered to the combustor model. During a test, the pressure in the heater remains constant. The heater fuel flow rate can be ramped to achieve a changing air temperature using a closed-loop control valve-flow meter system.

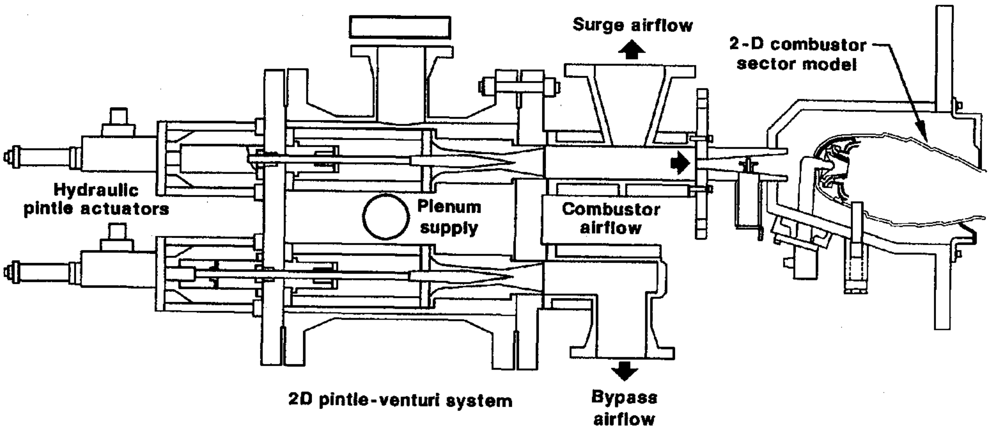


Fig. 4 Transient combustor airflow paths.

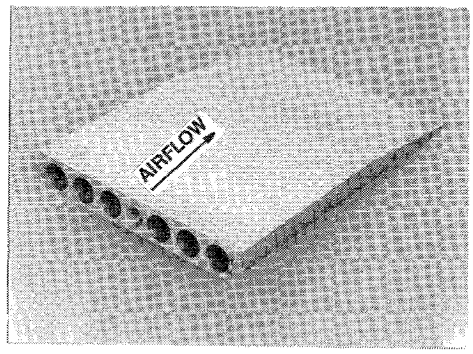
2) The heated air is delivered to a plenum which, in turn, supplies the test model airflow. An axisymmetric venturi, sized to operate choked, is located between the heater and the plenum to both isolate the heater from plenum pressure variations and to acoustically define the plenum volume. Since this venturi is choked and the heater pressure is held constant, the heater airflow rate varies inversely with the heater exit temperature.

3) The airflow to the combustor model is metered by a two-dimensional venturi containing a variable-position pintle centerbody. The pintle is always positioned to assure choked flow to the model. This condition establishes a clear upstream boundary condition to the test model. Ramp and oscillatory combustor airflow rates are achieved by repositioning the pintle in the venturi.

In an attempt to minimize pressure oscillations in the plenum, an identical two-dimensional venturi-pintle system exhausts a bypass flow from the plenum. The combustor pintle and bypass pintle are always actuated out-of-phase and with equal displacement to provide a constant total flow area through the venturi pair. Note that the equal displacement guideline is not as stringent as specifying that the two areas vary over the same absolute range (i.e., both having the same mean area); only the change in area must be compensated. This feature is useful to tailor the total airflow to the desired transient test. For example, the air heater may not operate stably at a very low airflow rate. Hence, for a low test model airflow rate, the bypass airflow can be set sufficiently high to raise the total flow rate and assure stable heater operation.

Each pintle-venturi system consists of a two-dimensional venturi with a wedged-shaped pintle (Fig. 5). Airflow approaches along the constant height portion of the pintle and passes through the minimum flow area (i.e., throat) at the pintle shoulder. The dimensions and angles of the pieces were specified to achieve a desired range of flow rates while retaining adequate positioning sensitivity when driving the pintle for low flow rate variations. The throat will always occur upstream of the minimum venturi body height. The divergence angle of the venturi body and the apex angle of the pintle were specified to assure a diverging flow area downstream of the shoulder. Assuming a plenum-to-combustor pressure ratio of 1.3, the minimum flow goal implied a nominal flow area of 1.5 in.^{2}. To assure adequate positioning sensitivity, it was desired to require a 0.1-in. pintle movement to achieve a 10% change in this area. This requirement was equivalent to achieving a linear area change of 1.5 in.^{2} per inch of pintle travel. As fabricated, the venturi width is 9.010 in. with a half-angle convergence of 4.8 deg. Together these dimensions yield an area change of 1.51 in.^{2} per inch of travel. The minimum venturi height is 1.360 in. and the maximum pintle thickness is 1.340 in.; the minimum pintle area is 0.180 in.^{2}. Each pintle is driven by a hydraulic actuator with a 6-in. stroke. The maximum pintle area is nominally 9.0 in.^{2}, which is consistent with the airflow goal at a high inlet air temperature and low rig pressure. Each pintle is guided with impregnated bronze bars along the venturi centerline. Holes were bored into each pintle to reduce its mass.

a)



b)

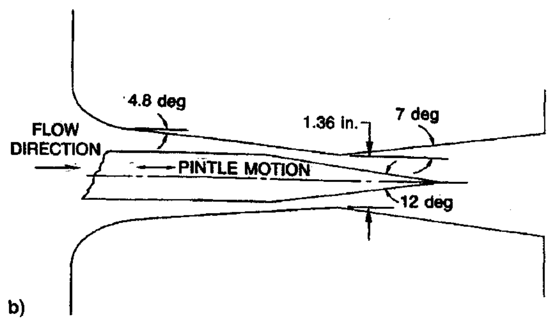


Fig. 5 Pintle-venturi system: a) pintle and b) pintle-venturi system.

The two venturi-pintle systems are contained within the plenum on a fixture designed to minimize the effects of assembly and thermal growth. As depicted in Fig. 4, the two venturi bodies are mounted to a cage structure that is bolted to the head end flange of the plenum; each pintle is driven on a shaft through this flange. This fixture was designed and toleranced to assure a quality alignment of each pintle in its venturi. The venturi does not attach to the downstream plenum flange; a sliding seal is accomplished by use of packing. By using a common fixture, the extent of pintle engagement in the venturi is not dependent on assembly factors such as bolt torque or gasket crush. Additionally, the cage bars produce a thermal growth in the venturi location similar to that expected for the pintle drive shaft.

The dynamics of the pintles were evaluated in specifying the actuation mechanism. The required pintle acceleration and force for candidate oscillations, and aerodynamic load (i.e., pintle drag) for particular operating conditions were computed. These analyses, and the consideration of the desired linear velocity and stroke for a pintle, led to obtaining a hydraulic actuation system rated at 60 gal/min at 3000 psi. This system, with a 60-gal tank, was sufficient to satisfy the flow and force requirements of the two pintle systems and the surge valve. A later evaluation of a particular surge transient indicated that greater aerodynamic pintle forces might be encountered. A pneumatic booster consisting of a 3.5-in.-diam piston contained in a cylinder was added to each pintle shaft outside the plenum. The cylinder is pressurized by the plenum. Then while aerodynamic force acts to engage the pintle into the venturi, the booster applies an opposing force to the shaft to offset the pintle drag.

Each pintle is driven by a Moog A085 servoactuator (1.1-in.^{2} area, 6-in. stroke) with the hydraulic flow regulated by a Moog 760-104A servovalve. The system employs closed-loop control for actuator position by use of a linear variable differential transformer (LVDT) for position sensing. The LVDT is excited and its signal conditioned by a Moog oscillator/demodulator (F123-204), which is fed to a Moog servoamplifier (F122-202). In operation, an instantaneously desired venturi area is computed from the set-point airflow rate and measured plenum conditions. This area is translated (by use of an area-voltage calibration) to a pintle position target signal that ranges between -10 to $+10$ VDC. The target is sent from the control computer to the servoamplifier that commands the servovalve to alter the hydraulic flow until the LVDT feedback matches the target position. A Hewlett Packard dynamic analyzer was used to characterize the response of the pintle system. In these tests, the analyzer delivered a fixed amplitude, sinusoidal voltage to the servoamplifier that began at 0.1 Hz and slowly increased until the test was completed. The LVDT feedback was received by the analyzer to determine the amplitude attenuation and phase-lag as compared to the target signal. Figure 6, taken from Ref. 1, depicts attenuation and phase-lag traces for a test with the combustor pintle system. The -3-dB bandwidth was 55 Hz; the system response up to the 10 Hz range of interest is sufficient to reliably produce controlled, oscillatory airflow transients.

4) An exhaust flow can be used to promote a periodic, reverse flow in the test model. This flow stream originates downstream of the combustor venturi, but upstream of the model. The valve (identified as the surge valve) can be actuated at the same frequency, but out-of-phase with the combustor pintle. Hence, when the delivery of combustor airflow is minimized, the exhausting flow is maximized.

The surge valve is a hydraulically-actuated, 8-in. butterfly valve with a maximum flow coefficient (Cv) of 2245. The valve is driven by an ExCello rotary actuator fed by a Moog 78 series servovalve. A potentiometer on the valve shaft, supported by United Technologies Research Center (UTRC) designed electronics, provides a feedback signal to another Moog servoamplifier to achieve closed-loop control of the surge valve angular position. The dynamic response of this valve was also investigated using the Hewlett-Packard Dynamic Analyzer and found to have acceptable amplitude and phase characteristics.

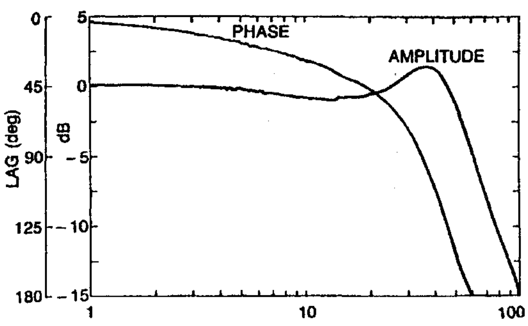


Fig. 6 Airflow pintle dynamics.

Air Heater Control System

The air heater fuel control system was obtained from Marotta Scientific Controls, Inc., and consisted of a LV53A valve, a Ramapo Mark V-1/2 flow meter, and an electronics control module (Fig. 7). The valve, an adaptation of a standard Marotta product, is an electrically operated, four-way proportional flow control device. It uses a integrally mounted solenoid valve to vary the instantaneous flow capacity of the valve. The flow meter employs a target mounted on a cantilever beam in the flow stream. The measured strain in the beam provides an indication of the drag on the target and, for known liquid density, an imposed flow velocity. This meter has the shortest response time of devices considered, with a quoted full response to a step change in 2 ms. The valve and meter capacity were specified for delivery of a liquid propane volume flow rate of up to 4.2 gal/min at a pressure drop of 100 psid. The electronic module provides closed-loop control for flow rate at the valve. That is, a target voltage corresponding to the desired flow is delivered to the module. The feedback signal from the flow meter is compared with the target, with the difference causing the solenoid to alter the valve capacity until the difference (or "error") is nulled.

A simple two-tier oxygen flow control was defined and used with the Transient Combustion Facility to supply the heater replenishment oxygen. In this approach, a fixed, gaseous oxygen supply pressure is available to two parallel paths. Each path contains an orifice sized to operate choked; one path also contains a shutoff valve. The line without the valve is termed the low flow path, and the valved line is termed the high flow path. If the temperature increases with time, the propane flow rate is initially low and only the low oxygen flow path is active; the valve is closed. When the control computer determines that the propane flow has exceeded a threshold, the valve is opened to also deliver through the high flow oxygen line. Appropriate combinations of supply pressure and orifice sets adequately match the replenishment oxygen flow rate to the propane flow rate for a transient test.

Test Model Fuel Control System

The test model fuel control system consists of three, independently controlled liquid fuel systems containing hardware similar to that contained in the heater fuel control system. Each contains a Marotta LV53a control valve, a strain-gauge-based flow meter, and an electronics module. Two of the systems contain flow meters with a range of 30–300 lbm/h, with the third system flow meter sized for 60–2000 lbm/h. Again, the electronic module provides closed-loop control of each flow at the valve as depicted in Fig. 7. The module receives the control system target voltage, compares it with the flow meter feedback, and sends an error signal to the control valve to cause it to achieve the desired flow rate. The system response is capable of tracking a 10-Hz sinusoidal oscillation without significant phase-lag or amplitude attenuation. A steam-fed heat exchanger is located in the fuel systems downstream of the control devices. Constant fuel

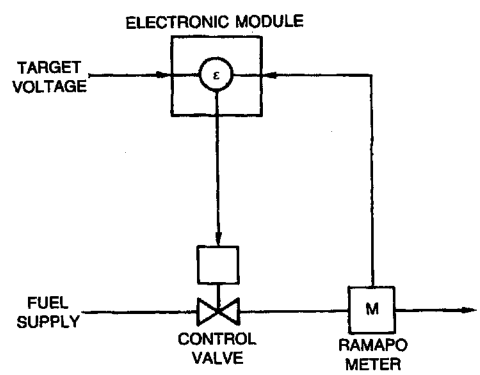


Fig. 7 Fuel control system.

temperatures up to approximately 300 F can be maintained even for large variations in the delivered flow rate.

Test Model Requirements

It is important to realize that in order to study the transient response of a particular system, the system dynamics must be preserved. For example, to study the transient response of a combustor, the burner must be contained in a volume representative of the actual application. This consideration requires that the test model case matches the combustor case, and that inlet and exit flows are acoustically isolated from the environment. Tests of a can combustor in a cylindrical case can satisfy the volume requirement while offering a structure easily suitable for high pressure. Sector combustors must be contained in a high-pressure sector case. The common practice used for steady-state testing of providing false walls around a combustor sector to define the flow path, and then mounting the assembly in a cylindrical pressure vessel, is unacceptable for transient testing; the response will likely follow the transient behavior of the pressure vessel.

Achieving acoustic isolation at the test model boundaries is also important to obtain the transient response of the model. The Transient Combustion Facility provides upstream isolation through the use of choked pintle-venturi systems. The test conditions and model hardware should provide the means to achieve a choked flow condition at the exit also. A water-cooled, two-dimensional exhaust valve is available with the Transient Combustion Facility to achieve the choked-flow boundary condition for combustor sector models (Fig. 8). The valve consists of a housing with a 3.7- by 12.0-in.-rectangular opening for the exhaust flow, and up to 10 vane-shaped, cooled pylons. The pylons mount to rails in the housing and can be arbitrarily spaced across the opening; fewer pylons can be used. Each pylon has a wedge cross section that establishes a series of minimum area slots for the flow. One version of the pylon contains four ports to accept total pressure or temperature instrumentation. The ports have a 0.16-in. i.d. and are equally spaced over the central 2.0 in. of the pylon.

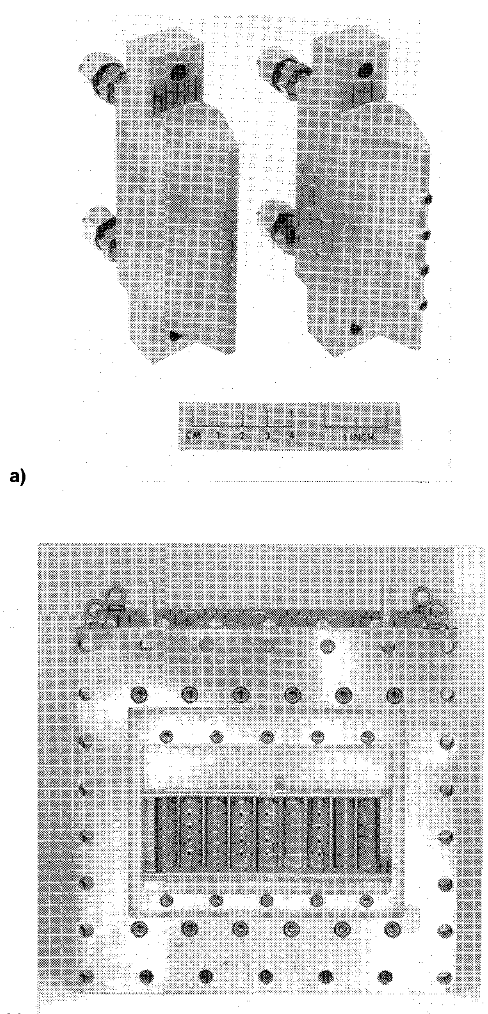


Fig. 8 Water-cooled exhaust valve: a) pylons and b) assembly.

Transient Combustor Studies

The Transient Combustion Facility has been evaluated to verify its capability to deliver controlled time-variations of air and fuel flow rate and air temperature to a combustor model,[1] and has been used to study the transient response of gas turbine combustor sector models. Two applications will be described: 1) the effect of transient fuel heating in the stem of an aerating fuel nozzle, and 2) the evaluation of a fuel-staged combustor during a cycle passing through its staging point. The former was part of a U.S. Navy-sponsored effort with Pratt and Whitney, whereas the latter is part of combustor research and development activity within UTC.

Verification of Capability

The capabilities of the Transient Combustion Facility have been verified in testing. These capabilities are well-illustrated by the results from an ambitious, isothermal airflow rate transient. During this test, the airflow delivered to a responsive model combustor began at a steady flow rate of 10 lb/s, and, in sequence, was linearly reduced to 5 lb/s in 1 s, held constant for 0.5 s, oscillated with 25% amplitude at 5 Hz for 1 s, held constant for 0.5 s, and stepped back to the original 10 lb/s. Figure 9 presents the pressure history, acquired at approximately a 1-kHz rate by a transient digital recorder (TDR), during the transient airflow profile. Every temporal flow feature of the airflow was achieved. The deceleration ramp was specified only by its endpoints, but during execution it consisted of 100 segments (10-ms duration) to assure a linear reduction. The dwell and oscillation periods, and oscillation frequency, matched the profile. The step change began abruptly and tracked the characteristic-time response of the model combustor. Results such as these established that the Transient Combustion Facility had the capability to uniquely study nonsteady-state flow phenomena.

Transient Fuel Heating in an Aerating Fuel Nozzle

Gas turbine fuel nozzles are required to inject fuel over the wide flow range that satisfies idle to sea level takeoff power requirements. Throughout this range, finely atomized and spatially distributed sprays must be produced. The aerating fuel nozzle satisfies these demands by using airflow momentum to control the spray quality. The fuel flow pressure loss is low and, hence, the fuel pressure in the nozzle is essentially equal to the burner pressure. This situation is in contrast to that existing in a pressure-atomizing fuel nozzle. This design

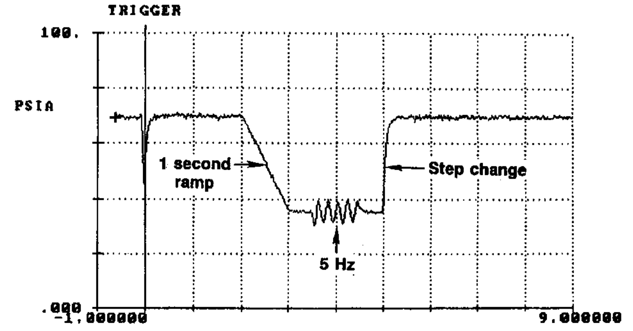


Fig. 9 TDR record of ambitious airflow variation.

uses the high momentum produced by high fuel flow pressure loss across the nozzle tip to atomize and distribute the flow; the fuel pressure in the nozzle greatly exceeds the burner pressure.

An important aspect of the fuel nozzle design is its ability to limit the temperature rise of the fuel flowing within it. The temperature of the fuel delivered to a nozzle is often greater than 250°F because of its use as a heat-sink for other engine systems. Any additional fuel heating is undesirable in order to avoid temperatures that promote fuel coking. The nozzle support stem is immersed in high-temperature combustor inlet airflow. Heat shielding and insulation in the stem limit the heat transfer to the fuel; while flowing, the fuel temperature rise is minimal. Similarly, heat shielding is used in the head of an aerating fuel nozzle to limit fuel heating from the atomizer airflow.

Operability concerns may exist for rapid fuel heating such as encountered when the fuel flow rate rapidly decreases to a low value in a snap-decel maneuver. In this instance, the heat transfer through the nozzle body to the fuel would be high while the flow rate would be low; high fuel heating rates might be encountered. For sufficient heating and low fuel pressure, the fuel would vaporize and displace the liquid from the nozzle. If this event is followed by a rapid accel, the vapor might collapse and interrupt the fuel delivery into the combustor, promoting a blowout. Fuel vaporization would be more likely to occur in an aerating nozzle than in a pressure atomizer because of the lower fuel pressure encountered in the nozzle stem.

Transient combustor tests were performed as part of a U.S. Navy sponsored study to determine burner conditions and nozzle configurations that result in a blowout during a decel-accel sequence (also known as a "Bodie"). A four-nozzle, advanced combustor sector was used; the sector was modified to admit excess airflow into its corners to eliminate preferential flame holding. Inlet airflow rate and temperature, fuel flow rate and temperature, and burner pressure and exit temperature were measured at a 30-Hz data rate. Tests were performed using either single-flow (one low-pressure drop fuel passage) or dual-flow (one low-pressure drop passage, one high-pressure drop passage) nozzles. The test fuels were JP4 and JP5 heated to 300°F.

Each test consisted of a sequence of three Bodie cycles (Fig. 10). For each, the burner air and fuel flow rates, and air temperature, began at a steady high-power level. In the first cycle, each of these parameters was synchronously ramped to a low-power level in 1 s, held at this level for 2 s, and ramped back to the high power level in again 1 s. At low power, the air and fuel flow rates were 40 and 60%, respectively, of the high-power condition. The second cycle began after a 2-s hold at the high-power level. This cycle was similar to the first except that the air and fuel flow rates at the low-power condition were only 30 and 40%, respectively, of the high-power levels. The third cycle achieved the same parameter values as the second cycle, except the air temperature remained at the high-power level into the low-power plateau. These three cycles progressively offered more favorable conditions for the occurrence of fuel vaporization in the nozzle. Cycle 2, with its lower flow rates, produced a lower burner pressure than cycle 1, and cycle 3 promoted fuel heating at this condition by extending the time period of nozzle exposure to high-temperature inlet air. Figure 10 is a data trace of these transient input parameters and illustrates that these three synchronized cycles were accurately produced by the Transient Combustion Facility.

Data from tests using JP4 fuel for combustors configured with either the dual-flow nozzles (Fig. 11) or single-flow nozzles (Fig. 12) illustrated the consequences of in-nozzle fuel vaporization.[2,3] Both figures trace the measured burner pressure; the transient airflow rate is included as a reference to the cycles. For test using the dual-flow nozzles (Fig. 11), the burner pressure recovered to the high-power level (following the low-power excursion) for each cycle. In contrast, the burner pressure did not recover following the low-power dwell of cycle 2 in tests using the single-flow nozzles (Fig. 12), indicating a combustor blowout.

The blowout during the test with the single-flow nozzles resulted from a momentary interruption of the fuel flow injected into the combustor. During the low-power dwell, in-nozzle fuel vaporization of the volatile JP4 occurred in the low fuel pressure circuit of this aerating nozzle and displaced the liquid fuel; vaporized fuel was being injected into the burner. At the beginning of the accel, the liquid fuel delivered to the nozzles repressurized the vapor and collapsed it. The time period required to restore the injection of liquid fuel into the burner represented an interruption in fuel flow. In

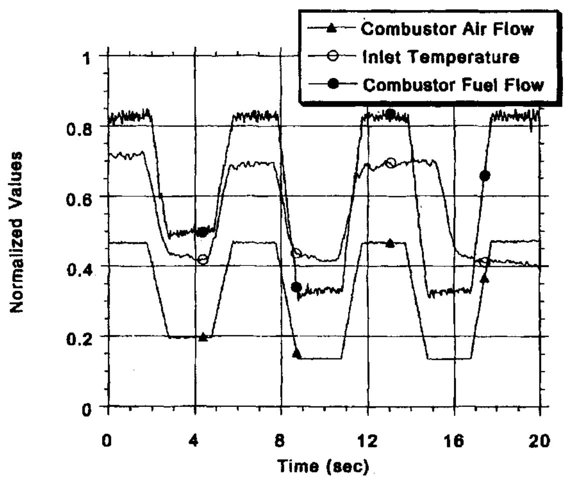


Fig. 10 Three-cycle Bodie transient.

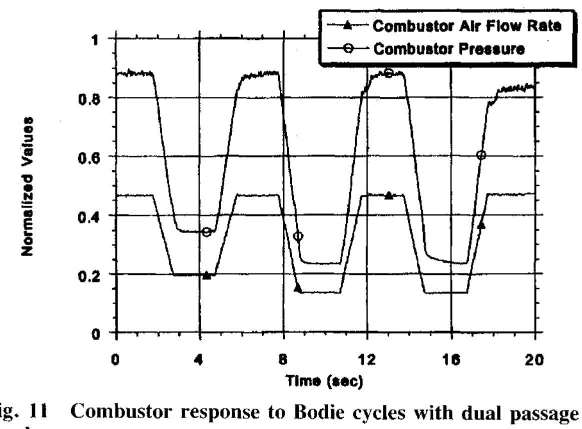


Fig. 11 Combustor response to Bodie cycles with dual passage fuel nozzles.

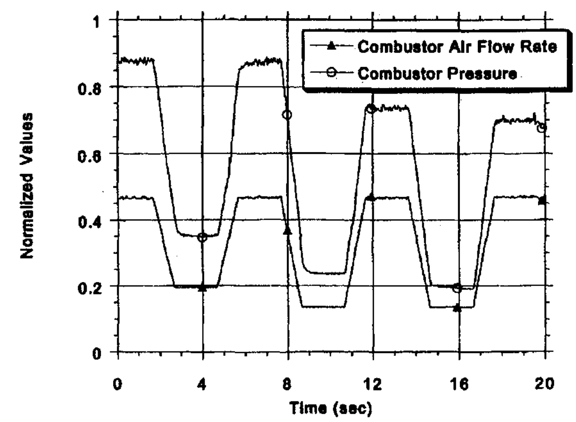


Fig. 12 Combustor response to Bodie cycles with single passage fuel nozzles.

contrast, the primary (high-pressure drop) circuit of the dual-flow nozzle sustained high fuel pressure and prevented vaporization. This sequence was as predicted by TRANSI, a time-dependent, lumped parameter model of a combustor[2] developed at Pratt and Whitney. In other tests, combustors fueled with JP5 did not blowout with either nozzle.[3] In this case, neither low fuel pressure nor longer exposure to high temperature inlet airflow was sufficient to promote the vaporization of this less volatile fuel.

Staged Combustor Transients

Modern combustor concepts seek to minimize emissions such as NO_x over a wide range of operating conditions. One strategy for reducing NO_x emissions involves fuel staging. In a fuel-staged combustor, there are multiple stages (two in this case) of fuel injectors. If only one stage of fuel injection were used at high engine power levels, the fuel/air ratio in the primary combustion zone could lead to temperatures high enough to form significant amounts of thermal NO_x. The fuel staging strategy seeks to solve this problem by distributing the fuel more evenly throughout the combustor at high power, so that the local peaks of fuel/air ratio (and therefore temperature) are greater in number, but significantly lesser in magnitude. At low power levels, the combustor would operate on one stage only, so that the lean stability characteristics of a nonstaged combustor would be maintained (primary zone temperatures at low power are low enough so that only minimal NO_x is formed).

If the combustor operates on one zone at low power, but two zones at high power, this implies that, as the engine accelerates, the combustor must make a smooth transition from one- to two-stage operation. During this transition, the secondary stage must be lit without affecting the engine performance in any way. Conversely, there must be a point during deceleration at which the secondary zone is turned off. Not only is a fueled zone of the combustor being turned on and off, but fuel is being shuttled back and forth between injection zones, depending upon the rate of increase of engine power level. The operability and performance of the combustor as it proceeds through these staging points are of crucial importance. For example, if one zone is too lean because it only receives 5% of the total fuel flow, it may blowout, leading to a 5% decrement in combustion efficiency, and a decrease in engine thrust. Staging schedules must account for the transient flight profiles of airflow and total fuel flow and also for the split of the fuel flow between the two zones at all points in the operating envelope.

For each transient flight event, the airflow, total fuel flow, and air temperature profiles follow a fixed path, dependent upon the nature of the flight maneuver. The staging strategy determines how the fuel flow is split between the two zones at any power level. It determines the point at which staging starts, and the rate at which fuel is shuttled between zones as the power level changes within the two-zone regime. Staging schedules must be evaluated based on their impact on the operability, emissions, and performance of the combustor relative to a single-stage combustor.

It is necessary, then, to characterize the transient operation of a staged combustor as it proceeds through these staging points and encounters the rapid shuttling of fuel between injection zones. Prospective staging strategies may be evaluated at a sector level in the Transient Combustion Facility. The ability to simultaneously control airflow, air temperature, and two separate fuel flows is used. Each fuel injection zone has its own dedicated fuel control system. The transient flow profiles of each fuel system can be varied to simulate different staging strategies for a given transient event.

One transient event of interest occurs when the airplane lands. Initially, the airplane is in its final approach condition. It then decelerates and loses altitude until it lands. Then, after a short delay, the pilot reaccelerates the engines to provide thrust reverse for braking. This entire process, known as an approach-touchdown-reverse transient, typically takes less than 20 s. During this event, it is crucial that the combustor respond smoothly and as expected. For the combustor, it results in "bucket" profiles for airflow, air temperature, and total fuel flow vs time (Fig. 13). That is, each parameter initially decreases over a few seconds, followed by a short hold and an increase. In a staged combustor, the fuel flow split between injection zones changes even more rapidly during both the deceleration and acceleration portions of the transient (Fig. 14). Initially, the fuel flow is split almost evenly between the primary and secondary zones. As the engine decelerates, the percentage of fuel flow to the secondary zone is decreased, and the percentage of flow to the primary zone is increased. The inverse of this happens again during acceleration. The application of the fuel staging schedule results in the zonal fuel flow rate profiles shown in Fig. 15. The two fuel flow rate profiles are controlled independently of each other, so that the total fuel flow rate at any instant is merely the sum of the two individually controlled zonal flows, and is not controlled explicitly. The "peaks" in total fuel flow rate profile (Fig. 13) result from a slight miscoordination of the two zonal profiles.

Figure 16 shows the average combustor exit temperature and combustor pressure response during an approach-touchdown-reverse transient cycle. Neither of these is explicitly controlled (only airflow, fuel flow, and inlet temperature are controlled), so they act as good indicators of the tolerance of the combustor to rapid fuel redistribution. Both the pressure and temperature react smoothly, in concert with changes in the total flows. Neither shows evidence of any staging effects during the deceleration or acceleration staging. It should be noted that the exit temperature profile reflects only the resultant total fuel flow profile; the peaks in temperature at the beginning and end of the transient are in response to the peaks in the total fuel flow profile. As expected, the pressure does not respond to these small spikes in fuel flow, and the com-

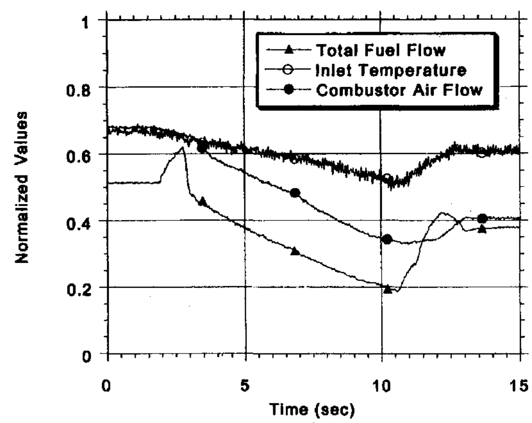


Fig. 13 Total flow profiles for approach-touchdown-reverse cycle.

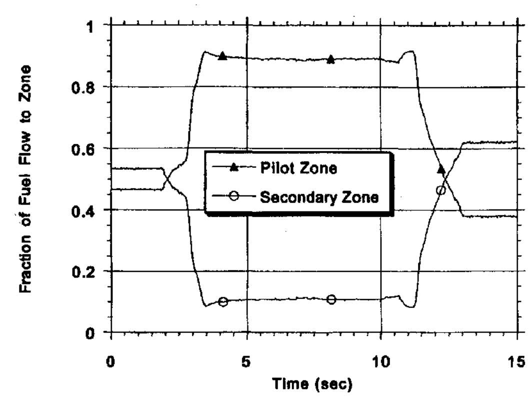


Fig. 14 Fuel staging schedule for approach-touchdown-reverse cycle.

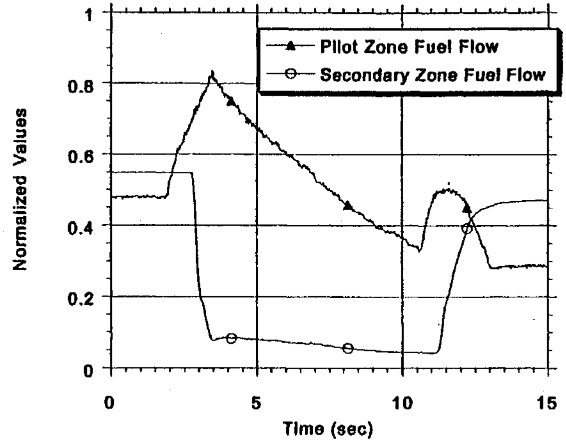


Fig. 15 Zonal fuel flows for approach-touchdown-reverse cycle.

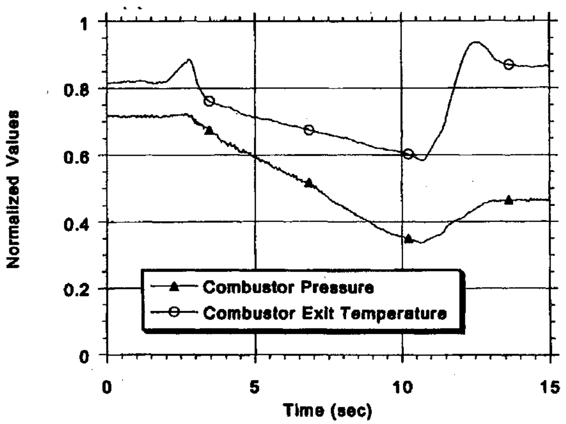


Fig. 16 Combustor response to approach-touchdown-reverse cycle.

bustor passes through them without any compromise of operability.

Summary

Successful development of advanced gas turbine combustors will likely require the evaluation of components and systems at both steady-state and transient conditions. The Transient Combustion Facility provides the opportunity to study the tolerance of a new design to transient operation during its evolution. Rapid, controlled time variations of air and fuel flow rates and air temperature can be delivered to a test model. This capability has been used to study combustor systems, particular components, and isolated combustor processes. A growing transient-response experience base will permit the design and development of more robust advanced gas turbine combustors.

Acknowledgments

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