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Effects of Ambient Conditions and Fuel Composition on Combustion Stability

Authors:

M.C. Janus (FETC-MGN)

G.A. Richards (FETC-MGN)

M.J. Yip (FETC-MGN)

E.H. Robey (EG&G Technical Services of West Virginia)

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ABSTRACT

Recent regulations on NO_x emissions are promoting the use of lean premix (LPM) combustion for industrial gas turbines. LPM combustors avoid locally stoichiometric combustion by premixing fuel and air upstream of the reaction region, thereby eliminating the high temperatures that produce thermal NO_x . Unfortunately, this style of combustor is prone to combustion oscillation. Significant pressure fluctuations can occur when variations in heat release periodically couple to acoustic modes in the combustion chamber. These oscillations must be controlled because resulting vibration can shorten the life of engine hardware.

Laboratory and engine field testing have shown that instability regimes can vary with environmental conditions. These observations prompted this study of the effects of ambient conditions and fuel composition on combustion stability. Tests are conducted on a sub-scale combustor burning natural gas, propane, and some hydrogen/hydrocarbon mixtures. A premix, swirl-stabilized fuel nozzle typical of industrial gas turbines is used. Experimental and numerical results describe how stability regions may shift as inlet air temperature, humidity, and fuel composition are altered. Results appear to indicate that shifting instability regimes are primarily caused by changes in reaction rate.

INTRODUCTION

The thrust for lower NO_x emissions has led to the increased use of lean premix (LPM) combustion in gas turbine applications. In LPM combustion, fuel and air are mixed upstream of the primary zone to avoid the locally high temperatures that accompany diffusion-style combustion and are known to produce thermal NO_x . The LPM style of combustion, however, is also prone to combustion oscillation.

Combustion oscillation can occur when variations in heat release periodically couple to acoustic modes in a combustion chamber. Oscillation can be thought of as a closed-loop interaction between combustion and acoustic processes. A variation in heat release produces an acoustic disturbance that is reflected by the combustor walls.

Although the magnitude of this pressure disturbance is reduced by acoustic losses, it can produce some change in the combustion process, thereby altering the heat release and closing the feedback loop. With correct timing of the feedback, and sufficiently small losses, the oscillation magnitude can grow to a limit-cycle oscillation. Compared to diffusion-style combustors, the LPM combustor is especially susceptible to these instabilities because acoustic losses and nozzle pressure drop are relatively small. Minimal acoustic losses are due to the absence of downstream dilution air holes; most of the air is deliberately sent through the fuel nozzle. Thus, much of the acoustic energy is reflected from the solid combustion liner walls. Small pressure losses are a necessary design requirement to ensure high thermodynamic efficiency, meaning that slight pressure disturbances can disrupt the flow of air (or fuel) with a subsequent variation in heat release. Regardless of their origin, these oscillations must be controlled because resulting vibrations can shorten the life of engine hardware (Cutrone et al. 1985).

Changes in instability behavior are typically attributed to combustor modifications or changes in operating conditions. In addition, laboratory and engine field testing have shown that instability regimes can also change with environmental conditions and fuel composition. These field observations have seldom been reported in the literature. A small number of laboratory studies have suggested that both fuel type and ambient conditions should affect combustion stability. Vandsburger et al. (1989) have shown that the oscillating behavior of step-stabilized flames was significantly different for various combinations of spray versus premixed gaseous combustion. Mehta et al. (1990) demonstrated the effect of fuel volatility on oscillations in aero-engine applications. In a study of oscillating (pulse) combustion, Keller et al. (1989) report that the oscillating frequency and amplitude will change with gaseous fuel composition. These results were readily explained by the change in chemical reaction time associated with the change in fuel type. Based on a theoretical model, Narayanaswami and Richards (1996) concluded that the ambient temperature will affect the oscillating characteristic of pulsating

combustion systems due to changes in the chemical reaction time and secondary changes in volumetric flow rates for a given mass flow. Rocket combustion stability is also known to depend upon the supply temperature of both fuel and oxidant (Hulka and Hutt 1995). Although none of these earlier studies are directly applicable to premixed, swirl-stabilized combustion, these citations suggest that both fuel composition and ambient conditions should be considered when evaluating combustion stability. This consideration prompted the current study of these parameters in a premixed combustion system.

We conducted tests on a subscale combustor that burns natural gas, propane, and hydrogen/natural gas mixtures. A premix, swirl-stabilized fuel nozzle typical of industrial gas turbines is used. Experimental and numerical results are presented that describe how stability regions may shift as inlet air temperature, humidity, and fuel composition are altered.

BACKGROUND

Mechanisms that contribute to variation in heat release are described for various combustion systems by Putnam (1971), Harje and Reardon (1972), Yang and Anderson (1995), Candel (1992), and Schadow and Gutmark (1991). Depending on the combustor application, mechanisms can include vortex shedding, periodic change in mixing rates, fuel system acoustic feedback, change in liquid fuel evaporation rate, and others. Although several of these mechanisms could play a role in swirl-stabilized, LPM combustion oscillation, a combination of experimental testing and numeric simulation at the Federal Energy Technology Center has identified five primary mechanisms. These mechanisms are air supply variation, fuel supply variation, mixture feed variation, swirl variation, and pilot variation. A description of these mechanisms can be found in Richards (1996).

The experiments described here likely involve instabilities due to mixture feed variation. As explained later, the experimental configuration is specifically designed to ensure the absence of air supply variation, fuel supply variation, and pilot variation. Furthermore, the ability to replicate the experimental instability behavior with a *one-dimensional* fluid model (Janus et al. 1996a, 1996b) indicates that swirl variation (i.e., vortex shedding) is an unlikely mechanism in our experiment. Successful simulation of vortex shedding would obviously require a *two-dimensional* model; this was not needed to simulate observed laboratory behavior. Given this, the relevant processes for this system are shown schematically in Figure 1 and described below.

In experimental tests and numerical simulations of this type of fuel nozzle, oscillations are observed at many operating conditions due to the variation in total mixture flow rate arriving at the flame front (Janus and Richards 1996a). Although the fuel and air stream are choked at the supply point, acoustic compression and rarefaction in the fuel nozzle barrel produce a fluctuation in the fuel/air flow rate. This can lead to a subsequent fluctuation in the heat release rate, even though the fuel/air ratio does not change. For example, if the oscillating combustor pressure were great enough, the nozzle mixture velocity could momentarily drop to zero. The combustion rate would then also decrease as the flame consumes the remaining mixture in the combustor. After a short time, the nozzle velocity would again increase as the combustor pressure drops, thereby injecting the accumulated mixture from the nozzle into the flame. If the resulting heat release and pressure fluctuation are in phase, the oscillation will

be driven according to Rayleigh's criterion (Rayleigh 1878). The mathematical statement of Rayleigh's criterion is

$$\frac{1}{T} \int_0^T \int_V P(\vec{x},t) \dot{Q}(\vec{x},t) dV > \text{acoustic losses} \quad (1)$$

The term on the left (referred to as acoustic gain) is the product of heat release and pressure fluctuations integrated throughout the combustor volume, and averaged over a time T , which is the oscillation period. This integral must exceed the acoustic losses if oscillations are to grow. The phase between P and Q plays a determining factor in the magnitude of this integral. If, for example, we consider the variables P and Q as simple sinusoids, then this integral will be maximized when P and Q are in phase, but minimized when out-of-phase. As described below, changes to this phase can be related to physical time scales for various processes.

To interpret the data, we modify an approach described by Keller et al. (1989, 1990). Keller showed that oscillating, premixed (pulse) combustion could be characterized by a fluid dynamic mixing time and by a chemical reaction time. Keller showed that the sum of the mixing and chemical reaction time determined the phase of the heat release Q relative to the resonant pressure wave P . In accordance with Rayleigh's criterion, changes to the phase were used to successfully explain observed changes in oscillating behavior with mass flow and fuel dilution.

Many of the physical processes that occur during the oscillating combustion studied here are similar to those reported by Keller. A characteristic mixing time is required for premixed fuel and air to combine with hot combustion products, and a characteristic reaction time is needed for subsequent reaction. Unlike the experiments reported by Keller, the premixed fuel and air require a significant *advection time* to travel down the nozzle barrel before entering the combustor (Figure 1). Thus, we define a transport time which is the sum of the three characteristic time scales:

$$\text{transport time} = \text{advection time} + \text{mixing time} + \text{reaction time} \quad (2)$$

If the transport time is such that an accumulated mixture pocket generates heat near the peak of combustor pressure, an oscillation will result if the acoustic gain is greater than the acoustic loss. It is significant to note that in Keller et al., the mixing and reaction times were of the same order of magnitude. For this reason, Keller et al. demonstrated that changes in fuel composition would lead to changes in oscillating behavior.

Very detailed studies would be required to quantify the time scales in Equation 2 for specific gas turbine applications. Although such detailed studies might prove beneficial, the goal of this initial investigation was simply to present oscillating data as a function of fuel composition and ambient conditions. We show that a characteristic time model (Equation 2) is useful to interpret the observed behavior, and we suggest that the chemical time is comparable to the advection and mixing time for the system studied here. A companion numeric model also shows that ambient temperature can influence the stability behavior through the chemical reaction time. Although these results cannot be easily generalized to specific gas turbine applications, they suggest that stability characteristics of a given combustion system will be affected by ambient conditions and fuel type. As shown later,

Mixture Feed Oscillations

FIGURE 1. SCHEMATIC REPRESENTATION OF PROCESSES OCCURRING IN "MIXTURE-FEED" INSTABILITY. THE PREMIX SUPPLY OF FUEL AND AIR IS CHOKED AND MIXED AT THE ENTRANCE POINT OF THE FUEL NOZZLE. VARIATIONS IN COMBUSTION HEAT RELEASE CAN OCCUR WHEN ACOUSTIC WAVES IN THE NOZZLE BARREL REDUCE OR INCREASE THE SUPPLY RATE OF FUEL/AIR MIXTURE.

changes to stability behavior can be explained qualitatively using Equation 2.

EXPERIMENTAL DESCRIPTION

The experimental combustor is shown in Figure 2. This atmospheric pressure combustor is designed to handle multiple premix fuel nozzles. The 8.0 cm I.D. combustor body is constructed of quartz and is mounted inside a 35.56 cm O.D. steel containment pipe. The multiple viewing ports of the containment pipe allow complete optical access to the flame zone. Oscillations are excited at the quarter wavelength of the 0.6 m combustor body. The resonant quarter-wavelength frequency varies with the combustor gas temperature, typically between 275 and 325 Hz.

A detailed sketch of the premixed, swirl-stabilized fuel nozzle is shown in Figure 3. A central 1.27 cm stainless steel tube supplies premixed fuel and air to the pilot flame on the nozzle axis. The pilot flame is lit with an internal spark electrode approximately 5.7 cm upstream of the nozzle exit. Note that for the results to be discussed, the pilot is used only during startup and not during testing. The pilot tube is surrounded by the LPM fuel and air. The LPM fuel and air are mixed approximately 100 cm upstream of the nozzle to ensure thorough mixing. Note that eliminating the pilot flow during testing and premixing the fuel and air upstream of the nozzle ensures that air supply variation, fuel supply variation, and pilot variation will not cause instability.

The lean premix gases enter the nozzle through two diametrically opposed tubes 21 cm upstream of the nozzle exit. The premixed fuel and air pass through a wire mesh flow-straightener and then through straight-finned swirl vanes angled 45 degrees from the nozzle axis. The nozzle is equipped with four fuel bypass ports, although the ports are not used during the testing described here. The temperature of the fuel/air mixture is tightly controlled by passing the air lines through a small electric furnace prior to mixing with the fuel. Premix

temperatures are measured inside the LPM nozzle, after mixing with the fuel. Humidity levels are controlled by injecting metered water upstream of the furnace. The geometry of the air-feed system and the elevated temperature in the furnace ensure that no liquid droplets enter the fuel nozzle. Air and fuel flows are metered using standard orifice runs. Water flow is metered using a commercial rotameter. For data presented here, the local supply of natural gas had the following approximate composition: 94% CH_4 , 4% C_2H_6 , 1% C_3H_8 , 1% inert, and higher hydrocarbons. Propane and hydrogen were standard commercial-grade gases.

Unsteady pressure is measured using a piezoelectric pressure transducer with a 12 kHz sampling frequency. It is mounted on the nozzle exit flange, very near the flame zone. Thermocouples measure the gas temperature at multiple locations, including the LPM port/nozzle interface and near the exit of the combustor body. Relative humidity is calculated from the ratio of supplied water to air flow rate.

Generation of consistent humidity levels proved very difficult. Although the small flow of water could be metered into the air supply, wetting of the injector surfaces led to irregular humidity over time. Because of these difficulties, humidity levels reported here were no more accurate than ± 10 percent. The facility air supply used desiccant dryers and supplied air with approximately 10 percent relative humidity (at 295 K, 72 F) for all tests where humidity was not deliberately added.

MODEL DESCRIPTION

Our numerical results are derived from the Premixed Combustion Oscillation Model (PCOM). (Development and verification of this model are detailed in Janus and Richards 1996a&b.) The model geometry and relevant variables are shown in Figure 4. PCOM is a simple, nonlinear model which represents the relevant processes occurring in a fuel nozzle and combustor which are analogous to current LPM turbine combustors. Conservation equations for the fuel

FIGURE 2. EXPERIMENTAL COMBUSTOR CONFIGURATION. THE FUEL BYPASS PORTS WERE NOT USED IN THE DATA REPORTED HERE.

FIGURE 3. LPM FUEL NOZZLE CONFIGURATION. AGAIN, THE NOZZLE BYPASS PORTS WERE NOT USED IN THIS STUDY.

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FIGURE 4. MODEL GEOMETRY AND RELEVANT VARIABLES. THE MODEL INCLUDES THE OPTION OF USING A BYPASS PORT AT POSITION "B" AS SHOWN. IN THIS REPORT, THE BYPASS PORT WAS NOT USED. ZERO OR ONE-DIMENSIONAL CONSERVATION LAWS ARE WRITTEN FOR THE REGIONS BETWEEN STATIONS U, B, I, AND E.

nozzle and combustor are developed from simple control-volume analysis, providing a set of ordinary differential equations that can be solved on a personal computer. Combustion is modeled as a stirred reactor, with a bi-molecular reaction rate between fuel and air. Steady flames, blowoff, and dynamic instabilities can all be observed, depending upon various parameters. The model *does not impose* a variation in heat release to simulate instabilities. Oscillations versus steady flames (or blowoff) are predicted as a function of the prescribed operating conditions, just as occurs in an actual combustor.

RESULTS AND DISCUSSION

A series of tests were conducted to determine whether inlet air temperature, ambient humidity, or fuel composition would affect combustion stability behavior. The experimental results are presented as stability maps. A stability map is a three-dimensional plot showing combustor root mean square (RMS) pressure versus air flow rate and equivalence ratio (ϕ). Data points for each map were collected in a similar manner. The air flow rate was increased from 9.6 to 21.2 g/s in increments of approximately 1.9 g/s. At each successive air flow rate, the equivalence ratio was increased from 0.65 to 1.0 in increments of 0.05. A small portion of each map was inaccessible due to limitations in the fuel supply system. Air flow rates and equivalence ratios were selected to ensure a wide range of transport times.

The following three subsections (inlet air temperature, humidity, and fuel composition) include a brief description of the test conditions, a collection of stability maps addressing the relevant variable, and a simple hypothesis to help explain the observed behavior.

Inlet Air Temperature

Experiments were conducted to determine the effect of inlet air temperature on combustion stability. For each case described, the geometry of the nozzle and the combustor remains constant. Inlet air temperature is measured by a thermocouple at the LPM port/nozzle interface.

Figures 5a through 5d show stability maps for inlet air temperatures of 273, 311, 339, and 367 degrees Kelvin (32, 100, 150, and 200 degrees F). Note that combustion oscillation may occur over the entire range of equivalence ratios, not just at fuel lean conditions. It is sometimes assumed that premix combustion will lead to oscillations only at very lean conditions. These results suggest that oscillations can occur over the range of equivalence ratios. Similar behavior has been reported by Shih et al. (1996) and Schadow and Gutmark (1991). Examination of these maps indicates that inlet air temperature can play a role in determining combustion stability behavior. The combustor is highly unstable over a wide operating range at 273 K (32 F) inlet temperature (Figure 5a), but relatively stable over that same operating range at 394 K (200 F) inlet temperature (Figure 5d). Comparison of all four figures reveals that the unstable region appears to be shifting along the air flow axis toward the lower air flow rates as the temperature is increased. A new unstable region also begins to appear at elevated temperatures in the high flow rate/low equivalence ratio corner of the stability map. We believe these trends can be attributed to change in transport time, as described next.

Consider a point very near the edge of the stable/unstable boundary in Figure 5b (15.4 g/s air flow, 0.8 equivalence ratio). This boundary point is associated with a specific transport time, which we will describe as the "boundary" transport time. This value represents a transport time for which the acoustic gain (produced by the phase between pressure and heat release) is essentially equivalent to the

acoustic losses in the system. As the inlet air temperature is increased at this same flow condition (see point in Figure 5c), the transport time changes and the operating condition becomes stable. The increased temperature decreases the reaction portion of the transport time. A second and lesser effect is that advection time decreases. This decrease is the result of the increased velocity associated with the same mass flow of lower-density (hotter) air. The combined reduction in reaction and advection time produces a transport time that is less than the boundary transport time. This new transport time represents a condition at which acoustic loss exceeds acoustic gain. The combustor thus operates stably.

Note that the stability boundary has not disappeared; it has simply moved to a new location on the map where the transport time again equals the boundary transport time. According to Equation (2), the boundary should move to a point where one or more components of the transport time increase enough to offset the decrease in the reaction component associated with the increased inlet air temperature. The advection component of the transport time will be greater at lower flow rates, as previously explained. This is believed to be the reason why the unstable region on the stability map appears to shift along the air flow axis toward the lower flow rates.

To provide further confirmation of the effect of inlet air temperature, Figure 6 presents numerical results for the combustor operating at an equivalence ratio of 0.75 and an air flow rate of 19.3 g/s (the upper right corner of the stability map in Figure 5). The model shows an abrupt transition to strong oscillation over a fairly narrow temperature range, and appears to predict the smaller instability peak that emerges with temperature between cases in Figures 5a and 5b. Although the exact magnitude of this transition is overpredicted, the model does indicate that air temperature affects stability behavior by altering reaction rates, and thus transport times. The temperature effect was further verified numerically by artificially altering the reaction rate in the model. The results confirmed that minor changes to the kinetic reaction rate could initiate the transition to oscillating combustion, mimicking the effect of increased air temperature. Again, we point out that significant changes to inlet air temperature may also affect the advection portion of the transport time due to changes in volumetric flow rate. Note, however, that the model indicates that this effect is minor in comparison to the change in Arrhenius kinetic rate.

Humidity

The effect of ambient humidity was investigated by introducing small amounts of water vapor into the air stream. Figure 7 shows the effect of humidity on the combustor RMS pressure for an air flow rate of 10.6 g/s and a series of equivalence ratios at 311 K (100 F) inlet air temperature. The "high" humidity case corresponds to 55 percent relative humidity (± 10 percent) and the low case to the standard facility air supply humidity of approximately 10 percent. In this particular case, increased humidity is shown to decrease the combustor pressure oscillation. The abrupt transition to instability occurring at low humidity appears to be delayed in the high humidity case.

Development of extensive stability maps at a specific humidity ratios is a challenge, given the extreme difficulty in precisely controlling humidity levels over a wide operating range. It was therefore decided to create "high/low" humidity maps. Figures 8a and 8b show high humidity cases at 311 and 367 K (100 and 200 F) inlet temperature, respectively. Figures 5b and 5d represent the corresponding low humidity cases at the same inlet temperatures, respectively. The humidity *ratio* was the same for both Figures 8a and 8b, meaning that

(A) 273 K (32 F) INLET TEMPERATURE

(B) 311 K (100 F) INLET TEMPERATURE

(C) 339 K (150 F) INLET TEMPERATURE

(D) 367 K (200 F) INLET TEMPERATURE

FIGURE 5A-D. STABILITY MAPS FOR NATURAL GAS FUEL AT VARIOUS INLET AIR TEMPERATURES. THE INLET AIR TEMPERATURE FOR EACH CASE IS LISTED WITH THE FIGURE CAPTIONS (A) - (D).

the ratio of water to air was the same. At the lower temperature (Figure 8a) this corresponds to a relative humidity of 55 percent. Comparing Figure 8 versus 5b and d, humidity is shown to have a modest effect on combustion stability.

The effect of increased humidity on reaction rates has not been systematically studied in the literature. The presence of additional water molecules will undoubtedly change the combustion chemistry. However, in the absence of definitive data, we consider just the additional heat capacity of the water molecules. Ignoring the chemical effects, the added heat capacity will suppress the peak temperature and therefore decrease the reaction rate. It is expected that the decrease in reaction rate should increase the reaction portion of the transport time,

and therefore shift the stability region along the air flow axis toward the higher air flow rates. Figures 8a and 8b marginally support this hypothesis, but ultimately are inconclusive. Although the precise effect of humidity is difficult to discern from this limited data, we conclude that humidity *can* effect combustion instability behavior. Further testing is required to accurately determine the effects on stability.

Fuel Composition

The effect of fuel composition was investigated by testing with varying proportions of natural gas, propane, and hydrogen. Fuel composition is expected to effect stability behavior by altering the reaction

FIGURE 6. NUMERICAL PREDICTION OF COMBUSTOR RMS PRESSURE VERSUS INLET AIR TEMPERATURE. NOTICE THE SHARP TRANSITION TO OSCILLATING COMBUSTION FOR A RELATIVELY MINOR CHANGE IN INLET AIR TEMPERATURE.

FIGURE 7. RMS PRESSURE VERSUS EQUIVALENCE RATIO FOR LOW (10%) AND HIGH (55%) RELATIVE HUMIDITY CASES.

(A) 311 K (100 F) INLET TEMPERATURE

(B) 367 K (200 F) INLET TEMPERATURE

FIGURE 8A-B. STABILITY MAPS FOR NATURAL GAS FUEL WITH HIGH RELATIVE HUMIDITY AT TWO DIFFERENT INLET AIR TEMPERATURES. COMPARE 8A AND 8B TO FIGURES 5B AND 5D.

rate and the volumetric flow rate. The effect of overall volumetric flow rate associated with different fuels influences the advection portion of the transport time.

Figure 9 is a stability map for a fuel mixture of 75 percent natural gas and 25 percent hydrogen (volumetric) at 311 K (100 F). Figure 9 should be compared to the stability map in Figure 5b, which represents 100 percent natural gas at 311 K (100 F). The natural gas/hydrogen mixture has a faster reaction rate and therefore a shorter transport time than that of 100 percent natural gas. It is expected that the natural gas/hydrogen map (Figure 9) would shift along the air flow axis toward the lower air flow rates in comparison to Figure 5b because the presence of hydrogen should have a similar effect to that of increased inlet air temperature. This hypothesis is supported by noting the visual similarity between the 100 percent natural gas map at 339 K (150 F) (Figure 5c) and Figure 9. An exact characterization of the reaction and advection times (as in Keller et al. 1990) is needed to make a definitive conclusion about the role of the reaction time.

Figures 10a through 10d show stability maps for propane for the same inlet temperatures as in Figure 5. (However, note the slight difference in inlet temperature for Figure 10a only.) Propane has a reaction rate that is faster than natural gas, and a volumetric flow rate that is lower than natural gas for a given equivalence ratio. Faster reaction rates translate to shorter reaction times, and lower volumetric flow rates translate to longer advection times. Comparison of Figures 5a-5d with 10a-10d reveals that the stability regions are visually similar. One could hypothesize that the counteracting effects of a shorter reaction time and longer advection time leave the transport times virtually unchanged. However, this conclusion cannot be drawn with the given data unless the components of the transport time are known precisely. Also note that the inlet air temperature effect is demonstrated once again by the propane stability maps.

We have shown that changes to ambient conditions and fuel composition manifest themselves as a change in the stability boundary.

Ambient conditions and fuel composition appear to have the greatest effect on the reaction time. These changes were evident in this combustor because the reaction time, as shown by Keller et al. (1989), was a significant proportion of the total transport time. This may not be true for arbitrary operating conditions and combustor geometries. If the transport time is dominated by the advection time or the mixing time, then the effect of the chemical reaction time will be reduced.

The idea of a boundary transport time is relevant to a combustion oscillation occurring with just one frequency near a single acoustic mode. If two acoustic modes exist, having different frequencies, then a boundary transport time will exist for each mode. In this situation, changes to the transport time may result in mode switching, rather than extinction or activation of oscillations.

For practical applications, these data suggest that it is important to test combustor stability with a recognition that ambient conditions and fuel composition may play an important role. Operation of a combustor near a stability boundary is likely to encounter oscillation problems with changes in environmental factors or fuel composition. Conversely, if the combustor can be designed to operate well-removed from the stability boundary, these effects should be minimal.

CONCLUSIONS

This study indicates that gas turbine manufacturers and users should be aware of the effects of ambient conditions and fuel composition on combustion oscillation. Combustor stability performance may vary unexpectedly due to changes in geographic climate, seasonal weather, or with fuel composition.

Transport time is a key parameter in determining stability performance. Transport time is the summation of advection time, mixing time, and reaction time. Changes to ambient conditions or fuel composition will alter transport times, and consequently will shift the position of instability regions on an operating map of nozzle air flow versus equivalence ratio. Performance changes are dependent upon

FIGURE 9. STABILITY MAP FOR NATURAL GAS/HYDROGEN MIXTURE. HYDROGEN WAS ADDED AT 25% BY VOLUME OF THE TOTAL FUEL SUPPLY. INLET AIR TEMPERATURE: 311 K (100 F). THE EQUIVALENCE RATIO (Φ) IS FOR THE TOTAL MIXTURE.

(A) 279 K (42 F) INLET TEMPERATURE

(B) 311 K (100 F) INLET TEMPERATURE

(C) 339 K (150 F) INLET TEMPERATURE

(D) 367 K (200 F) INLET TEMPERATURE

FIGURE 10A-D. STABILITY MAP FOR PROPANE FUEL. EXCEPT FOR 10A, THE INLET TEMPERATURES AND FLOW CONDITIONS CORRESPOND DIRECTLY TO THE NATURAL GAS STABILITY MAPS SHOWN IN FIGURE 5.

the proximity of the operating condition to the instability region. Ambient and fuel composition effects will most likely be noticed only if operating close to an instability boundary.

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- Figure 1. Schematic representation of processes occurring in "mixture-feed" instability. The premix supply of fuel and air is choked and mixed at the entrance point of the fuel nozzle. Variations in combustion heat release can occur when acoustic waves in the nozzle barrel reduce or increase the supply rate of fuel/air mixture.
- Figure 2. Experimental combustor configuration. The fuel bypass ports were not used in the data reported here.
- Figure 3. LPM fuel nozzle configuration. Again, the nozzle bypass ports were not used in this study.
- Figure 4. Model geometry and relevant variables. The model includes the option of using a bypass port at position "b" as shown. In this report, the bypass port was not used. Zero or one-dimensional conservation laws are written for the regions between stations u, b, i, and e.
- Figure 5a-d. Stability maps for natural gas fuel at various inlet air temperatures. The inlet air temperature for each case is listed with the figure captions (a) - (d).
- Figure 6. Numerical prediction of combustor RMS pressure versus inlet air temperature. Notice the sharp transition to oscillating combustion for a relatively minor change in inlet air temperature.
- Figure 7. RMS pressure versus equivalence ratio for low (10%) and high (55%) relative humidity cases.
- Figure 8a-b. Stability maps for natural gas fuel with high relative humidity at two different inlet air temperatures. Compare 8a and 8b to Figures 5b and 5d.
- Figure 9. Stability map for natural gas/hydrogen mixture. Hydrogen was added at 25% by volume of the total fuel supply. Inlet air temperature: 311 K (100 F). The equivalence ratio (ϕ) is for the total mixture.
- Figure 10a-d. Stability map for propane fuel. Except for 10a, the inlet temperatures and flow conditions correspond directly to the natural gas stability maps shown in Figure 5.