Summary of Results of Sensing and Active Control of Blowout

Synopsis

Work performed to date has demonstrated two key program deliverables (1) that the proximity of a combustor to blowout can be sensed, and (2) that this information can be used with an active control system to prevent blowout. Based upon these results, we have initiated discussions with a potential Phase III partner, Woodward Industrial Controls. Woodward is one of the leading manufacturers of fuel nozzles and ignitors for jet engines (both military and civilian). In addition, they make a variety of fuel flow control hardware.To date, we have had 3 telecons and one face to face meeting with Woodward, CFDRC, and Georgia Tech. In addition, Woodward is currently working on commercializing an ion sensor for combustor health monitoring to integrate with their fuel nozzles. Woodward expressed strong interest in incorporating the active blowoff control system into their hardware. In particular, they are interested in using their ion probe as a sensor, and their spark system and fuel valves as actuators for control. Their interests have focused some of the further active control demonstrations we have worked on with this project.

Test Hardware

Figure 1 shows an illustration of the lean premixed injector that has been used for the test program performed during this SBIR. The injector is designed to be mounted on the end of an 8" air supply line for easy integration in the lab at Georgia Tech. Air enters the injector from the back side where swirl is created using 10 contoured swirl vanes. Fuel is supplied to the injector via two 0.5" supply lines the feed a circumferential manifold that has 10 radial fuel injection spokes located just downstream of the vane. The fuel and air mix inside an annulus before being injected into a combustor. The injector is 4" in diameter and approximately 8" long (including fuel supply lines). The design features an integrated electrode along the centerline. A simple rod is shown in the Figure, but multiple configurations have been tested throughout the program.

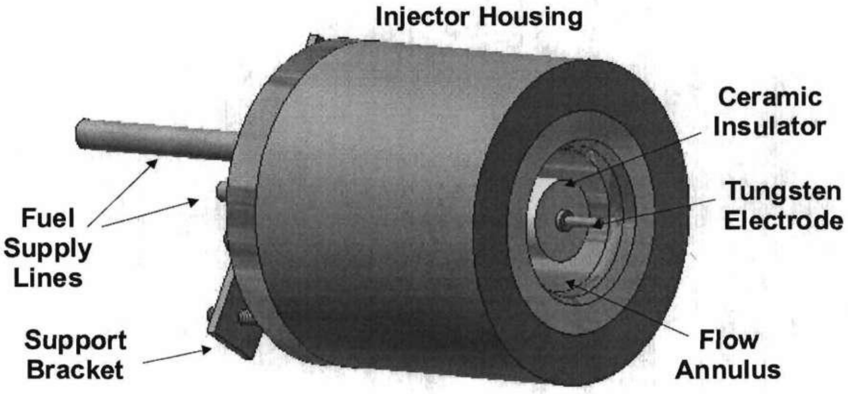

Figure 1. Pre-Mixed Natural Gas Injector Assembly.

Figure 2 and Figure 3 shows the combustor can and fuel injector assembly that is being used to test the premixed fuel injector with the corona discharge system. The combustor can has three quartz glass windows located at 90° intervals and 3 pressure taps located at different axial location opposite one of the windows.

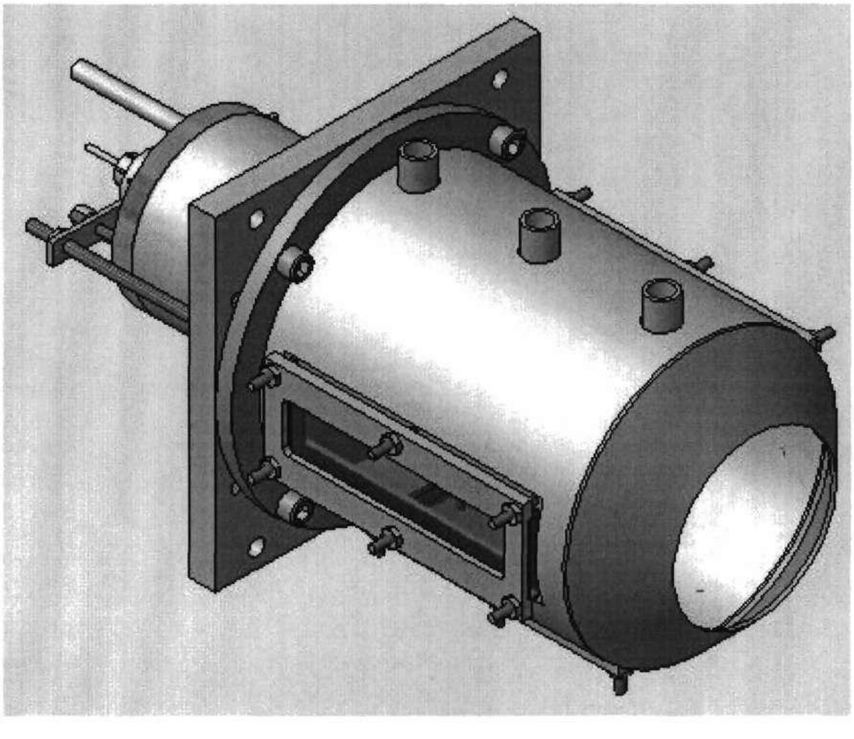

Figure 2. Combustor Can and Injector Assembly.

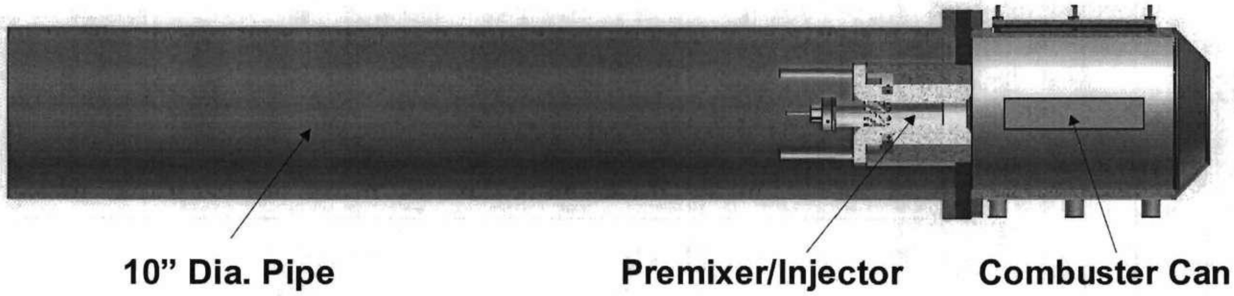

Figure 3. Entire Test Setup at Georgia Tech

Blowoff Sensing

In results to date, we have demonstrated that blowoff precursors can be sensed using three methods: acoustic (i.e., listening to the flame), optic (i.e., looking at the flame), or ion probe (i.e., the electrical conductivity of the flame). A typical demonstration using the ion probe is shown below for a stable flame (Figure 4, left) and one near blowoff (Figure 4, right). The erratic nature of the signal near blowoff is clearly evident.

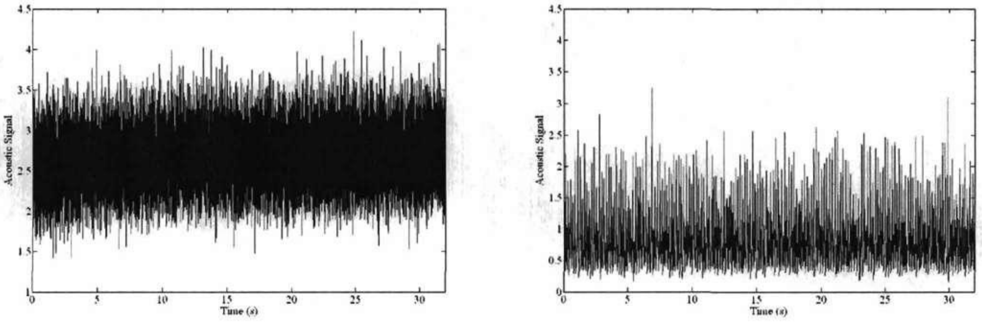

Figure 4. Typical time series from the acoustic probe indicating a stable flame (left) and one near blowoff (right). The blowoff events are clearly seen in the right image.

We have developed a variety of methods to extract and quantify these blowoff precursors, including spectral, wavelet, and statistical techniques. For example, using a wavelet filter, the proximity to blowoff can be monitored by determining the frequency of occurrence of these blowoff precursors, as shown below for acoustic data:

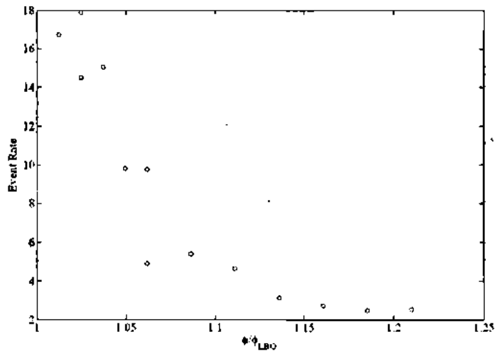

Figure 5. Dependence of frequency of occurrence of blowoff precursors upon fuel/air ratio. The rise in these events near blowoff provides a fast, effective method for sensing that the flame is near blowoff.

Blowoff Actuators:

We have explored two actuation methods for preventing blowoffs: fuel control, and electric discharge. For the discharge control method, we have looked at both spark discharge and corona discharge (the key difference between the two is a spatially concentrated vs spatially distributed discharge for ignition). Based upon our conversations with Woodward, we have focused on the spark system, as these are systems of direct interest to them. In addition, we found the spark system to be more effective at preventing blowoff in high velocity streams due to the concentration of energy in a smaller spatial region. Thus, in work below we have focused on fuel control and the spark system for blowoff control

Blowoff Control

As discussed above, we have demonstrated three sensors for detecting active control, and two actuators for preventing it. As such, there are at least 6 possible permutations of control based upon which sensing and control method is used – more permutations are possible if multiple systems are used together (such as fusing data from multiple sensors). This is illustrated in the figure below

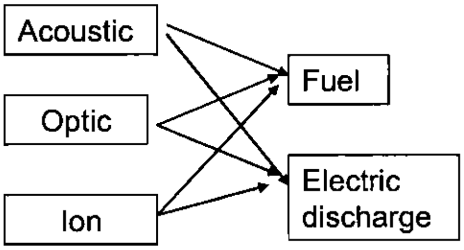

Figure 6. Chart demonstrating at least 6 possible means of blowoff control, based upon sensor-actuator combination. We have demonstrated control with several of these combinations to date.

In work to date, we have demonstrated control using several of these methods, in order to demonstrate that blowoff control is very feasible and can be done in a variety of ways. Moreover, these methods were chosen so as to utilize practical methods that are of interest to potential phase three commercialization partners. In the illustrative examples below, the blowoff control system was exercised by abruptly increasing the air flow rate into the system; this is, for example, a crude simulation of the flow oscillations encountered during a compressor surge.

Optic - Spark Control

Figure 7 shows this operating condition at a constant level for the first few seconds of operation. As the combustor is stable at this point, there is a low signal on the alarm counter at this point.

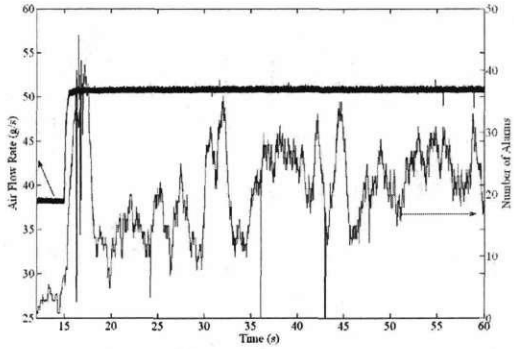

Figure 7: Variation of air flow into the combustor (blue). The green line represents the alarms sensed by the microphone

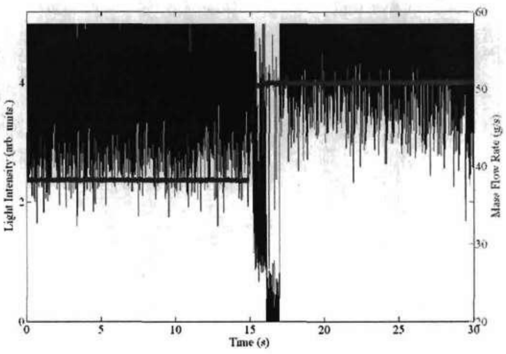

Figure 8: Optic Sensor Response. The mass flow rate of air is also indicated to provide an indication of the operating condition

Subsequently, the air flowing into the combustor is rapidly increased – this is accompanied by a sharp rise in blowoff alarms. The control system senses the problem and turns on the spark – this can be seen by the blip in the air flow signal due to electrical interference – this stabilizes the flame. In addition, the controller directs the fuel control system to provide more fuel into the combustor, to provide a sustainable fuel/air ratio, see Figure 9. Once the controller is confident that the flame is stable, it turns the spark back off. The controller then fine tunes the fuel flow rate, see Figure 9.

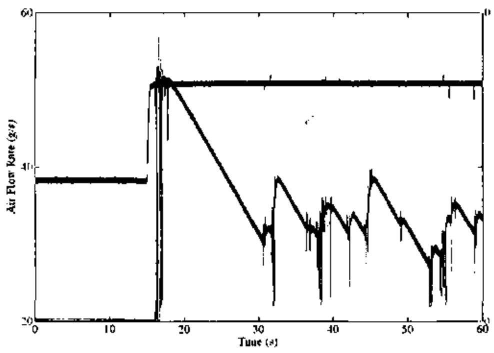

Figure 9: Depiction of fuel actuation

Acoustic-Fuel Control

In this demonstration, the air flow rate was abruptly increased into the combustor. If no control would have been applied, the combustor would have blown out. In this demonstration, the proximity of the system to blowoff was sensed with acoustic alarms and used to increase the fuel flow rate correspondingly. All of this control was done completely automatically – no human intervention was done. This sequence, showing the air flow rate increase, followed by the subsequent fuel flow response to maintain a stable flame is shown below.

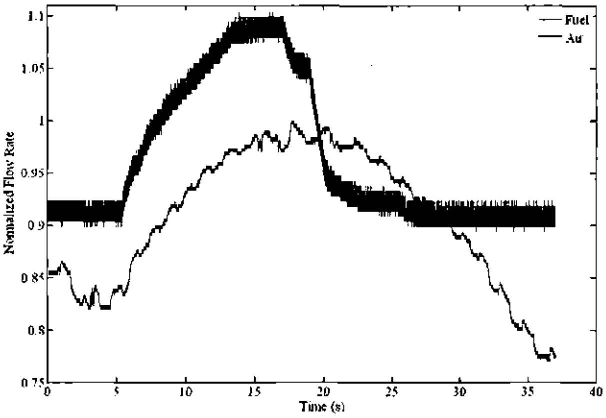

Figure 10: Demonstration of active control using acoustic sensing and fuel flow.