Active Combustion Control Using a Fluidic Oscillator for Asymmetric Fuel Flow Modulation

Daniel Guyot[*], **Christian Oliver Paschereit**[*] **and Surya Raghu**[†]
[*]Technische Universität Berlin, Müller-Breslau-Str. 8, D-10623 Berlin, Germany
daniel.guyot@tu-berlin.de
[†]Advanced Fluidics LLC, 4217 Red Banana Way, Ellicott City, MD 21042, USA
sraghu@advancedfluidics.com

Abstract

Fluidic oscillators are of special interest for fuel-based active control schemes featuring high frequency fuel flow modulation, as they are much more durable then conventional valves due to the absence of fast moving parts. In this work the performance of a fluidic oscillator in an active combustion control scheme is demonstrated. The oscillation frequency was controlled by varying the inlet mass flow of the oscillator. High speed camera recordings and hot wire measurements were performed to investigate the fluidics' oscillation characteristics. The oscillator was then incorporated into a bluff body burner, where it modulated parts of the fuel flow blended with nitrogen. Pressure and heat release fluctuations in the combustor were recorded and images of the flame were taken. At stable combustion the spectra of the heat release signals showed a clear peak corresponding to the fluidics' oscillation frequency, thus validating the ability of the oscillator to influence the combustion process. When operating the combustor at conditions that featured a strong low-frequency combustion instability, applying fuel modulation resulted in attenuation of the combustion instability for some oscillation frequencies. The attenuation was highest when modulating the fuel flow in between the fundamental instability frequency and its subharmonic. The results obtained in this work show that the fluidic oscillator in use allows for fuel modulation and hence combustion control without the need for complex and fast moving parts, thus ensuring a long actuator lifetime. This makes the fluidic oscillator highly appropriate for application in industrial gas turbines.

1. INTRODUCTION

1.1 Active Combustion Control

Active combustion control has been an extensively investigated method to improve the dynamic stability and emissions performance of gas turbine combustors for more than 50 years [1–3]. Especially since the introduction of low NOx lean premix combustion in modern low-emission stationary gas turbines, active control has received increasing attention. This is attributed to the susceptibility of this combustion mode to high amplitude pressure pulsations, also referred to as combustion dynamics or thermoacoustic instabilities [1–5], with typical pulsation frequencies in the order of one hundred to several hundred hertz.

Active control schemes have proven to be very effective in damping combustion oscillations [6–10]. Additionally, active control is much more adaptable to changes in the combustor operating conditions (for example due to varying fuel composition or load) than passive damping techniques. In 2005, Dowling and Morgans [11] completed an extensive review of active combustion control.

Active control schemes make use of sensors to observe and actuators to influence the combustion process and/or the acoustic field. Common sensors are microphones detecting pressure oscillations in the combustion system and optical probes monitoring the flame's chemiluminescence as a measure of its heat release. Most actuators rely on fuel flow modulation or acoustic forcing. While acoustic forcing with loudspeakers is very common under atmospheric conditions, only few combustion test facilities allow for acoustic forcing at elevated pressures (for example with siren actuators or valves modulating the combustion air).

In more industrial-like applications, one of the key requirements for active combustion control systems is compact, robust, low-cost actuators that are capable of high-frequency operation with an appropriate actuation authority. These requirements can usually not be met by acoustic forcing mechanisms. Instead, fuel flow modulation is in the majority of cases the actuation mechanism of choice, because of the fuel's high chemical energy content and hence actuation authority as well as its availability in a combustion system.

During the last decade, numerous research groups have designed and tested active combustion control systems incorporating one or more valves to modulate the primary or secondary fuel flow into gas turbine combustors. Many of them used on-off valves because of their general robustness and their low initial costs. More recent works also employed high-frequency proportional valves of different kinds to allow for more advanced fuel modulation. Overviews of different controllers incorporating valves are given by Seume et al. [12] and Schuermans [13].

Despite all this work, there are still only a few examples where these controllers are actually incorporated into fielded industrial gas turbines [11,12]. Kiel [3] and Dowling and Morgans [11] even identified actuator technology as the limiting factor in many combustion control applications. This is mainly for the following reasons: Additional fuel flow controllers add complexity to the turbine control system and may be another potential source of failure; due to their fast moving parts and hence high mechanical wear, the limited lifetime of their valves in the harsh turbine environment is usually much shorter than typical service intervals for industrial gas turbines1; and they increase the initial costs, especially if high frequency proportional valves are to be used. For the above reasons, an actuator mechanism that is simpler than a high frequency valve, but still allows for fuel flow modulation at around 100 Hz and above, would be desirable.

1.2 Fluidic Oscillators

One means of achieving fuel flow modulation at high frequencies without any fast moving components is through the use of fluidic oscillators. Being solid-state structures, these actuators can operate in and survive the harsh conditions found in gas turbine combustors, provided an appropriate material is selected.

Early works on fluidic technology were already conducted in the 1970's, though the development focused mainly on small signal logic control devices, whose primary function were to output binary pressure signals while bearing little flow load. Later investigations studied, for example, the application of fluidic devices in automotive engine gaseous fuel injectors and windshield washer nozzles.

The application of fluidic actuators for liquid fuel turndown in turbine engines was preliminarily explored by Brundish et al. in 1998 [14], but the work did not address issues associated with realistic combustion control such as fuel injection against high pressure gas and adequate frequency response. In 2002, Sun et al. [15] demonstrated a fluidic valve designed for liquid fuel modulation in gas turbine combustor applications with a maximum frequency of 100 Hz. However, they did not perform any combustion tests with their fluidic device.

Raman et. al [16,22,23] have developed several miniature fluidic oscillators mainly featuring a flipflop characteristic similar to the fluidic oscillator used in this work, but with oscillation frequencies in the kHz range. Their more recent applications include the suppression of jet-cavity interaction tones, mixing control in jets, and jet thrust vectoring.

2. FLUIDIC OSCILLATOR DESIGN AND OPERATION CHARACTERISTICS

2.1 Design of the fluidic oscillator model

A first fluidic oscillator model has been designed, fabricated and tested. A fluidic oscillator is a nomoving parts device with a supply port and one or two outlet ports. If a constant liquid or gas flow is injected into the supply port, a flow instability induced by the fluidics' internal geometry and the resulting flow field result in an oscillating flow at the outlets. A schematic of the generic fluidic oscillator used in this work is shown in Figure 1. In additional to the supply and the two outlet ports, the fluidic oscillator features a power nozzle, a control port, a chamber, and two feedback channels.

---

[1] In a typical gas turbine inspection interval of 24,000 hours a valve operating at 100 Hz would, for example, have to safely undergo almost 9 billion operation cycles, which is beyond the capability of most valves used in active combustion control systems [11]. However, several research groups are working on new valve systems to overcome these problems [25,26].

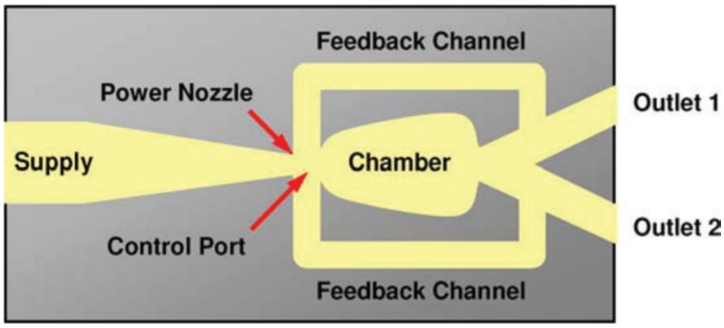
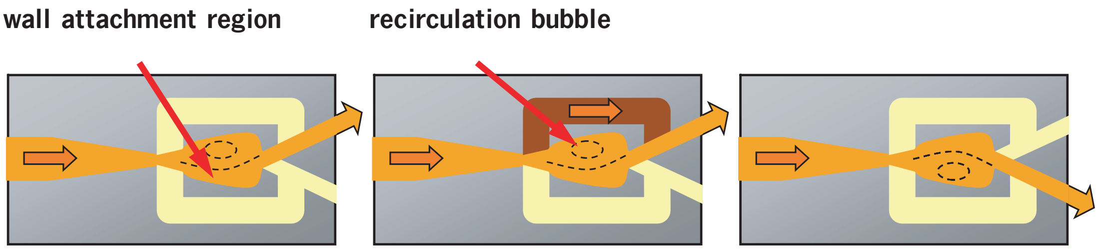


Figure 1. Sketch of the fluidic oscillator.

Figure 2 illustrates the underlying oscillation mechanism in more detail. The jet created in the power nozzle at the end of the converging supply section is bi-stable in nature. It passes through the control port and attaches to one side of the wall attachment region (here the lower one) provided in the chamber due to the Coanda effect (Figure 2 a). While the main flow is exiting the fluidics through outlet 1, the entrainment of fluid from the downstream end of the upper feedback channel causes suction in this feedback channel towards outlet 1. As a consequence, a low pressure wave is transmitted back through the feedback channel (Figure 2 b) to the control port, where it switches the jet attachment from one side to the other side of the chamber (Figure 2 c). This causes the exiting jet to switch to outlet 2. Thus an oscillatory flow is created at the two outlets switching continuously from one outlet to the other. Note again that only the supplied fluid is moving here, while the fluidics is completely motionless, and that in one oscillation cycle two jets are generated, one at each outlet.



a) b) c)

Figure 2. Operation mechanism of a fluidic oscillator.

The characteristics of the fluidic oscillator greatly depend on the design of the internal geometry of the wall attachment region and the feedback channels. Typically, fluidic oscillators have a linear flow versus frequency characteristic until sonic conditions at the converging section occur and show saturation beyond the corresponding flow rate. For a fixed internal geometry and a constant flow rate at the supply port, the oscillation frequency depends on the length of the feedback channels. In the present case, the overall dimensions of the fluidic device were 100 mm × 40 mm. The alternating jets exited from two 1/8 inch NPT tapped holes at the end of the fluidic device. The inlet flow was through a 1/4 inch NPT tapped hole. The actuator was designed and fabricated by Advanced Fluidics Corporation. More detailed information on the design and operating mechanism of fluidic actuators can be found in [16-19].

Previous investigations by Guyot and Paschereit [20,21] have shown that asymmetric premix fuel modulation in a swirl-stabilized combustor by means of two on-off valves has the same, if not higher, capability as symmetric fuel modulation to suppress combustion oscillations. By generating two asymmetrical oscillating mass flows, while maintaining constant overall mass flow (through the supply port), the fluidic oscillator model has essentially the same effect as two on-off valves when operated asymmetrically.

2.2 Operation characteristics of the fluidic oscillator

a) Oscillation Tests with Water

The fluidic actuator's capability to generate an oscillating flow was tested at ambient conditions (approximately 20°C, no combustion) for three fluids: water, natural gas, and nitrogen. To visualize the oscillation of the fluidics' outlet jets, the fluidics was first mounted in front of a high speed camera (with the outlets facing upwards) and water was injected into the supply port.

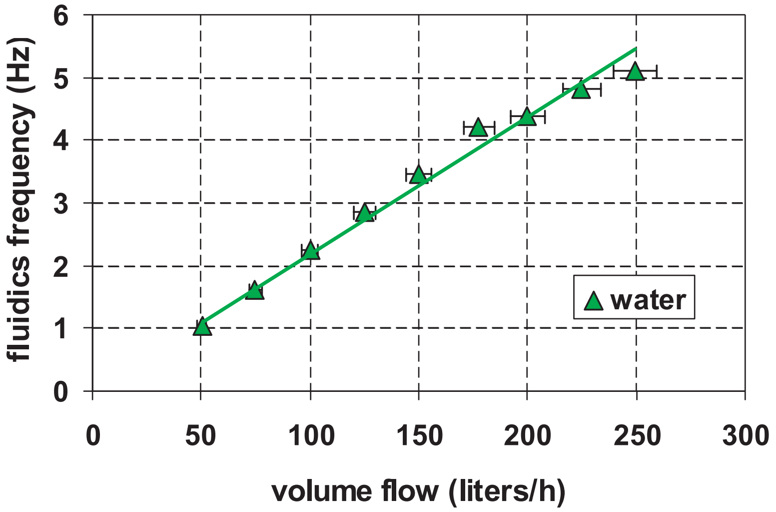


Figure 3. Fluidics water flow rate vs. fluidics oscillation frequency obtained from the high speed camera images.

Water flow rates between 50 and 250 liters per hour were investigated. At each flow rate, a 30 second movie of the oscillating flow was acquired with the camera. The images were evaluated to obtain the fluidics (oscillation) frequency. The results are shown in Figure 3. The fluidics frequency ranges from 1.0 Hz to 5.2 Hz and increases approximately linearly with the water flow rate.

Figure 4 presents a selection of the camera images captured of the oscillating outlet jets. The three columns correspond to water flow rates of 150 (left), 200 (middle), and 250 liters per hour (right), while the rows correspond to different phase angles of the oscillation. At zero phase angle, the right outlet jet is just about to start exiting.

Four main observations can be made in the images:

1. As to be expected, the height reached by the outlet jets and hence their velocity increases with the water flow rate.
2. Due to the internal design of the fluidics, the water jets at the two outlets oscillate asymmetrically to each other.
3. One outlet closes completely in between two consecutive jets, that is, the velocity of the exiting jet goes down to zero and the water jet stops. In this sense, an on-off oscillation is generated at each outlet. The time response of the jet velocity will be investigated more closely for the gas test (see next subsection).
4. The water flow rate does not affect the general structure of the oscillation. Apart from the outlet jets' height, the shape of the jets for different flow rates looks similar for one phase angle within the water flow range investigated.

b) Oscillation Tests with Gas

The water tests were conducted mainly for the purpose of visualizing the fluidics oscillation. However, the fluidic oscillator was specially designed to generate an oscillating gas flow in an atmospheric combustor. The intended frequency range was 30 to 200 Hz. Therefore, the fluidics' capability to generate oscillations at such frequencies was tested for two gases: natural gas, the intended fuel for later combustion tests, and nitrogen, which is inert in the combustion process. Natural gas mass flows of 1.0 to 7.0 kg/h and nitrogen mass flows of 1.0 to 10.0 kg/h were investigated. Two hot wire probes were placed 10 mm downstream of the fluidics' two outlets to measure the velocity of the exiting jets.

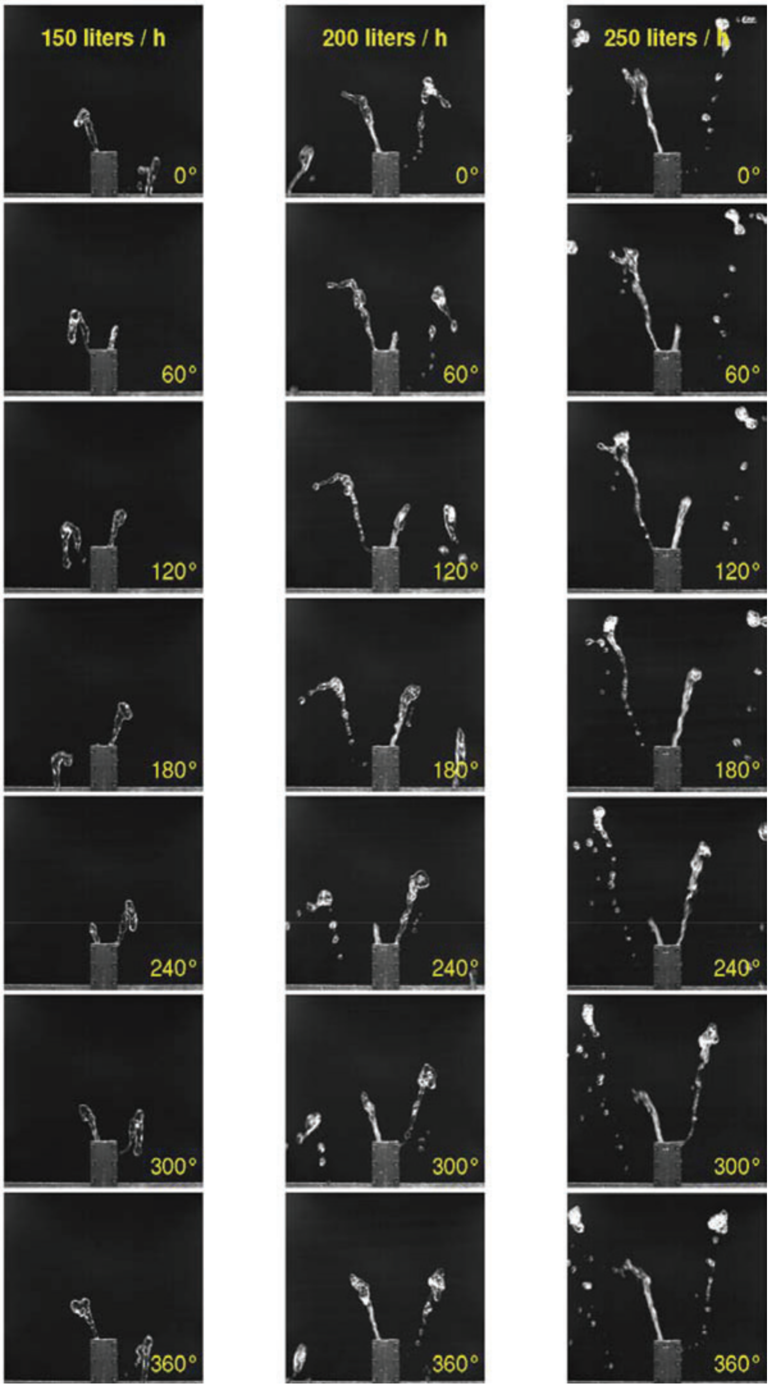


Figure 4. High speed camera images of the fluidics' oscillating water jets captured at different oscillation phase angles for water flow rates of 150 (left), 200 (middle), and 250 liters per hour (right).

As an example, the phaseaveraged time traces of the velocity fluctuations for nitrogen mass flows of 2, 5, and 8 kg/h are plotted in Figure 5. The average is based on approximately 1000 recorded cycles. As in the water tests, the asymmetry of the velocity oscillation at the two outlets can clearly be seen in the velocity time traces. The fluctuation at each exit closely resembles an onoff characteristic with maximum velocities of up to 20 m/s and minimum velocities of 0 m/s.

Increasing the mass flow through the fluidics as well as feeding the fluidics with natural gas instead of nitrogen resulted in higher oscillation frequencies. These trends can be seen in Figure 6 a, where the dominant oscillation frequency is plotted versus the fluidics mass flow. Within the mass flow ranges investigated, the minimum and maximum oscillation frequencies for both gases were in the order of 30 and 200 Hz, respectively, as desired. Additionally, the oscillation frequency increased approximately linear with increasing mass flow. The same mass flow rate resulted in higher oscillation frequencies for natural gas, due to its lower density, when compared to nitrogen injection.

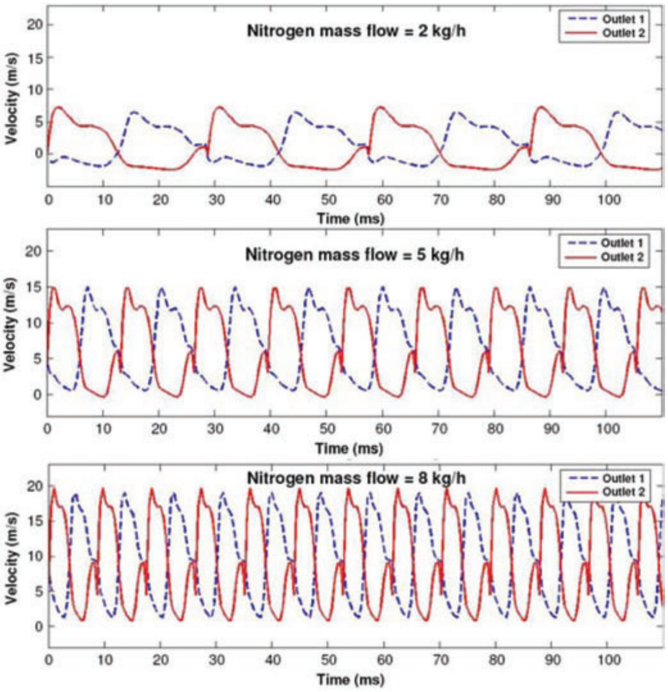


Figure 5. Phase averaged time traces of the velocity fluctuations measured at the fluidics' outlets for a nitrogen mass flow of 2 kg/h (top), 5 kg/h (middle), and 8 kg/h (bottom).

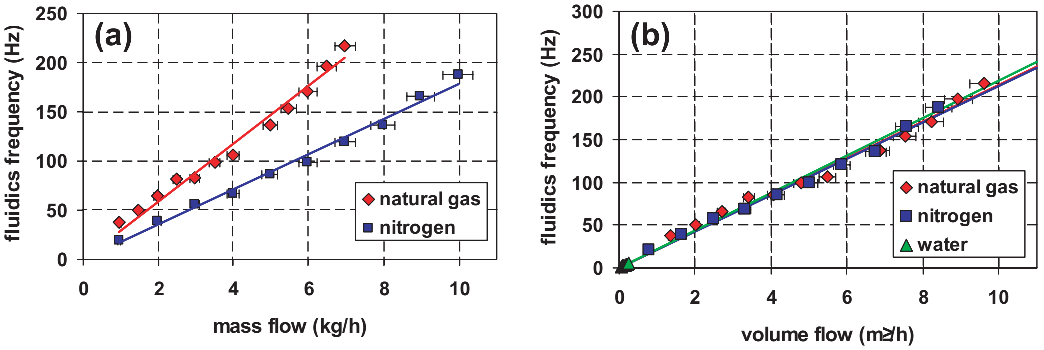


Figure 6. Oscillation frequency of the gas flow exiting the fluidic actuator as a function of the supplied mass flow (a) and volume flow (b).

Plotting the fluidics frequency versus the volume flow rate of the gas feed into the fluidics' supply, as shown in Figure 6 b, revealed approximately the same linear increase with the flow rate for both gases, natural gas and nitrogen. Also the trend line obtained from the water tests agrees remarkably well with the gas trend lines and data points, even though the investigated water flow range was 0.05 to 0.25 m^3/h, while the gas tests were conducted between approximately 1 and 10 m^3/h. From the results presented in Figure 6, it can be concluded that the oscillation frequency of the fluidics is primarily a function of the volume flow rate within the investigated flow rate range.

For the application of the fluidic oscillator in a combustion system, it is important to control the actuation frequency and amplitude. This can be achieved as follows:

The oscillator's actuation amplitude corresponds to the natural gas mass flow that is modulated by the fluidics. The actuation frequency corresponds to the fluidics' oscillation frequency. For a constant actuation amplitude (i.e., constant natural gas mass flow), the actuation frequency can be adjusted by blending the natural gas mass flow with additional nitrogen, thus increasing the fluidics volume flow. The more nitrogen is added, the higher the actuation frequency. Hence, the fluidics' actuation amplitude and frequency can be controlled independently by controlling the natural gas and nitrogen flow fed into the fluidics supply.

Note that the minimum frequency of oscillation is given by the selected natural gas mass flow, and that blending the natural gas flow with nitrogen does not only increases the fluidics frequency, but also the outlet jet velocity. Note also that two jets are generated in one oscillation cycle, one at each outlet.

3. COMBUSTION TESTS WITH IMPLEMENTED FLUIDC OSCILLATOR

3.1 Bluff Body Burner Set-Up with Fluidic Oscillator

For a first assessment of the fluidic oscillator's ability to influence a combustion process by modulating a fraction of the fuel flow, the fluidics was implemented into a simple bluff body burner. Figure 7 shows two sketches of the bluff body burner with attached fluidic oscillator (a,b) and a photo of a typical flame for this burner (c). The bluff body is supported by a ring structure. The main fuel is injected through 40 boreholes, each 1.1 mm in diameter, which are distributed equidistantly along a tube fixed to the upstream end of the bluff body. The bypassing air stream takes the fuel into the recirculation zone downstream of the bluff body, where it is burnt. As shown in Figure 7 c, the flame observed in the combustion experiments was anchored in the recirculation zone at the downstream end of the bluff body.

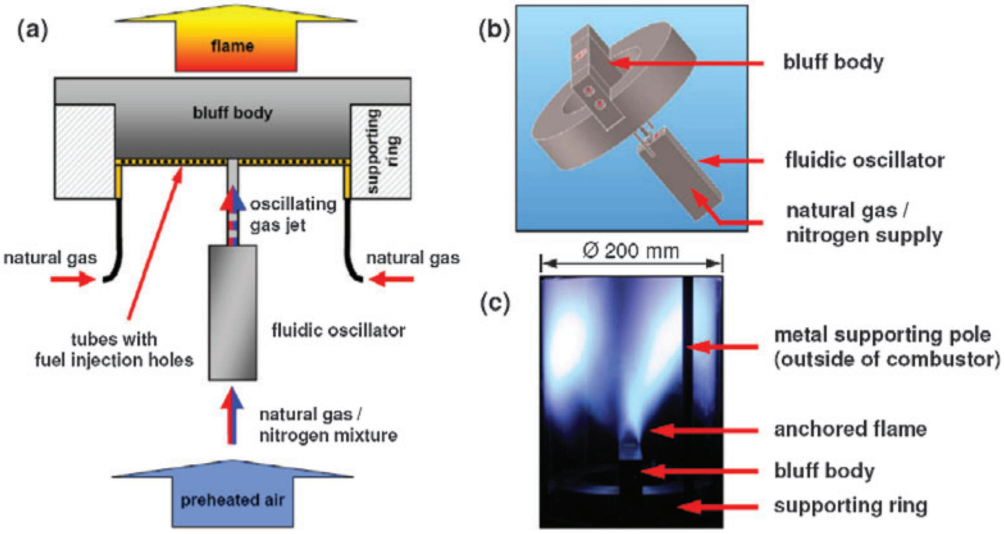


Figure 7. Assembly of the bluff body burner and fluidic oscillator (a,b) and a photo of the resulting flame (c).

To allow for fuel flow modulation, the fluidic oscillator was attached to a metal pole of 50 mm length, which was mounted in the middle of the bluff body's upstream edge. Fuel flow modulation was achieved by feeding a fraction of the main fuel into the fluidics supply (blended with nitrogen if required). The fluidics was positioned in a way which ensured that gas from one fluidics outlet passed the bluff body only on one side, while gas from the other outlet passed the bluff body only on the other side. This flow behavior was confirmed with test in which the fluidics was supplied with smoke.

3.2 Combustion Test Facility

All combustion results presented here were obtained in the atmospheric combustion test facility shown in Figure 8. Combustion air is supplied via a preheater. The facility has a 300 mm long air-cooled quartz glass combustion chamber with an inner diameter of 200 mm that allows for optical access to the flame. A water-cooled resonance tube of the same diameter and 1050 mm in length is attached to this combustion chamber. The resonance tube consists of two parts connected by flanges. The downstream part is equipped with five water-cooled microphone holders. In case of combustion instabilities, the selected length of the resonance tube results in a quarter wave mode with an oscillation frequency close to those typically found in full-scale engines. Figure 8 also shows the three supply lines for the bluff body burner configuration: natural gas for the burner's main fuel supply; nitrogen and natural gas for the fluidic oscillator. Each supply mass flow was controlled by an individual mass flow controller.

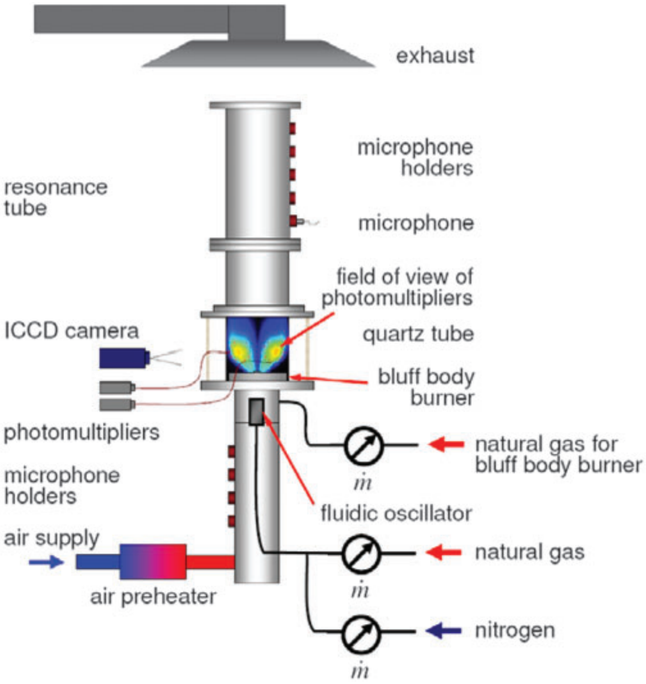


Figure 8. TU Berlin combustion test facility.

Pressure oscillations in the combustion chamber were measured using a condenser microphone placed into the most upstream microphone holder of the resonance tube. The heat release oscillation was measured using two photomultipliers equipped with narrow band-pass filters centered at 308 nm. At this wavelength, the photomultipliers captured the flames light emission associated with OH* chemiluminescence, which is assumed to be proportional to the heat release [22]. Additional to the photomultiplier, an ICCD camera also equipped with narrow band-pass filter centered at 308 nm was employed to record the spatial heat release distribution of the flame.

3.3 Flame Response at Stable Combustion in the Bluff Body Burner

To investigate the response of the combustion process to fuel flow modulations generated by the fluidics, especially the heat release in the flame, the bluff body burner was first operated at conditions where the combustion process was stable when injecting all the fuel through the burner's injection tubes (no fuel modulation). At this stable operating or reference condition, the pressure and heat release fluctuations in the combustion chamber were recorded. Note that the fluidics was already assembled to the burners, but not activated (that is, no gas was supplied to the fluidics).

To activate the fuel flow modulation, a fraction of the main fuel was redistributed to the fluidics supply. The overall fuel and air mass flows and hence the equivalence ratio were kept constant. If required, additional nitrogen was added to the fluidics' supply flow for control of the oscillation frequency. The amount of added nitrogen was always less than 5% of the combustion air. Hence, its impact on the combustion process can be considered to be negligible.

A power of 80 kW with an overall equivalence ratio of $\phi = 0.6$ and an air inlet temperature of 290 K (no preheating) was selected as the stable reference point. At these conditions, only broadband noise was evident in the OH* chemiluminescence signal. Note that two photomultipliers were employed to observe the OH* oscillation of one half of the flame (see Figure 8), that is, at one side of the bluff body. Then, the fluidics was activated by redistributing 16% of the main fuel (that is 1 kg/h of natural gas) to the fluidics supply (no change of the overall fuel flow rate, no blending with nitrogen). For this fluidics flow rate, the oscillation frequency of the fluidics was found to be 31 Hz when tested in cold conditions (see Figure 6). Indeed, the spectrum of the recorded OH* signals also features a dominant peak at 31 Hz, that is, the heat release was fluctuating at the oscillation frequency of the fluidics.

To increase the fluidics' oscillation frequency without having to inject more fuel (and thus changing the actuation amplitude), the fluidics gas flow was blended with nitrogen. The nitrogen mass flow was increased in steps of 0.5 kg/h up to 4.5 kg/h. The response of the heat release is shown in Figure 9 and Figure 10. In Figure 9, the OH* spectra for selected nitrogen mass flows between 0 and 2 kg/h are plotted. Figure 10 presents the dominant OH* oscillation frequency as a function of the total volume flow (natural gas and nitrogen) for all nitrogen mass flows investigated. As the frequency of the velocity fluctuation at the fluidics' outlet presented in Figure 6 (hot wire tests), the recorded OH* oscillation frequency increases linearly with the fluidics' volume flow. Moreover, the trend found for the OH* oscillation frequency with the fluidics' volume flow is identical to the trend derived from the hot wire tests (compare Figure 10 and Figure 6 b). These findings verify that it is indeed the natural gas modulated by the fluidic actuator that causes the oscillation of OH* and hence heat release in the flame. Also note that the oscillation amplitude remains constant (Figure 9).

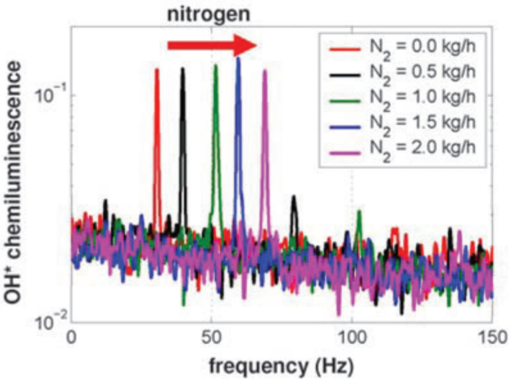


Figure 9. Spectrum of the OH* chemiluminescence signal for different nitrogen mass flows.

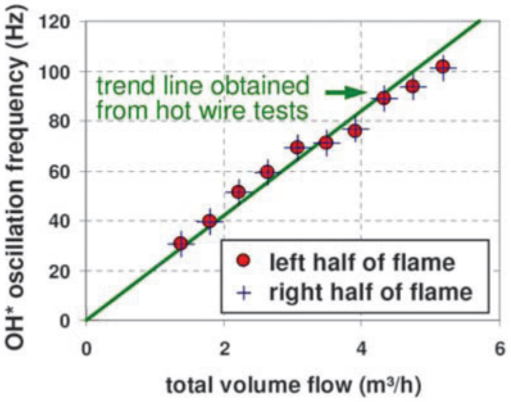


Figure 10. Frequency of the dominant peak in the OH* chemiluminescence spectrum (recorded by the two photomultipliers) vs. the total volume flow (natural gas and nitrogen) feed to the fluidics' supply.

3.4 Active Combustion Control in the Bluff Body Burner

After the capability of the fluidic oscillator to force heat release oscillations onto the stable combustion process had been verified, the bluff body burner was operated at operating conditions with strong combustion oscillations in case of deactivated fuel flow modulation (no gas flow through the fluidics). Starting from these baseline conditions, the fluidic oscillator was activated (as in the stable combustion test) by redistributing a fraction of the main fuel to the fluidics supply, while maintaining a constant overall equivalence ratio. The oscillation frequency was varied by blending the fluidics natural gas flow with nitrogen.

To assess the impact of fuel flow modulation on the combustion process, the ratio of the pressure rms obtained for different actuation amplitudes (that is, fluidics natural gas mass flows) and frequencies with respect to baseline conditions was analyzed. An overall equivalence ratio of $\phi = 0.6$ and an air inlet temperature of 400 K were selected. The combustor's power was set to 120 kW, which corresponds to an overall fuel mass flow of 9 kg/h. At these baseline conditions, the combustor exhibited a combustion instability with a dominant pressure oscillation frequency of 128 Hz. This frequency corresponded to the quarter-wave of the first longitudinal mode in the combustion system.

Fuel modulation was then activated. Two different ratios of fluidics to overall gas mass flow were tested: 17% and 21%. As before, the fluidics' actuation frequency was varied by blending the fluidics gas flow with nitrogen. Note again that for each oscillation cycle of the fluidics, two gas jets exit the actuator, one at each outlet. For an oscillation frequency of 60 Hz, for example, 120 gas jets per second were injected into the combustor. However, two consecutive jets were injected asymmetrically, that is, on opposite sides of the bluff body.

The impact of fuel modulation on the combustion oscillations is presented in Figure 11, which shows the normalized pressure rms with respect to baseline conditions as a function of the fluidics frequency. For most oscillation frequencies fuel modulation resulted in reduced pressure pulsations. Attenuation of the pressure rms was highest (above 40%) for fluidics frequencies of 80 to 110 Hz and 160 to 185 Hz, when the frequency of natural gas injection did not match the instability frequency or its harmonic. At these conditions, modulated fuel injection disrupted the thermoacoustic feedback cycle, which resulted in lower pressure pulsations. This mechanism was already observed in other (more industrial-like) burner configurations [1,20].

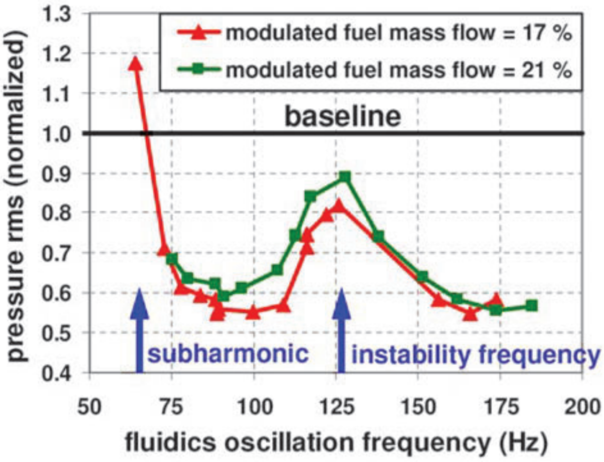


Figure 11. Normalized pressure rms vs. fluidics oscillation frequency.

In the case of modulation at the instability frequency itself, the attenuation was lower, though the pressure pulsations were still below baseline conditions. In contrast, when the fluidics frequency approximately matched the subharmonic of the unstable mode, fuel modulation did not suppress the instability, but increased it. Consequently, the instability was amplified by up to 22%. The observed reduction of the pressure rms when operating the fluidics at the instability frequency can be explained when considering that in each fluidics oscillation cycle two gas jets are generated by the fluidics, one at each outlet. While the gas jets exiting at one outlet might well lock with the instability feedback cycle and enhance the combustion oscillations, the jet exiting at the other outlet will be exactly in anti-phase for this case, thus interfering with the feedback cycle. The combination of these two effects seems to result in an overall reduction of the pressure rms with respect to baseline conditions.

These results indicate the capability of the fluidic actuator to generate fuel oscillations that interfere with the combustion oscillation in a thermoacoustically unstable system.

4. CONCLUSION

In this work the performance of a fluidic oscillator without fast moving parts in an active combustion control scheme was demonstrated. The oscillator was tested in a bluff body burner configuration, where it modulated parts of the fuel flow. The oscillation frequency was controlled by varying the inlet mass flow of the oscillator.

The fluidic oscillator has one inlet and two outlets. While maintaining a constant inlet mass flow, the fluidics' outlet mass flow oscillated asymmetrically between the two outlets. The fluidic oscillator's ability to generate an oscillating flow was verified without combustion. Water, natural gas, nitrogen and mixtures of the latter two were fed into the oscillator's supply. High speed camera recordings and hot wire measurements showed that the oscillation frequency at the outlets is a function of the volume flow rate through the oscillator supply. Oscillation frequencies of up to 220 Hz were observed within the investigated flow range.

The oscillator was incorporated into a bluff body burner, where it modulated parts of the fuel flow blended with nitrogen. Pressure and OH* chemiluminescence oscillations in the combustor were recorded and images of the flame were taken. The OH* response of the flame to fuel flow modulation was first studied during stable combustion. The spectra of the heat release signals showed a clear peak corresponding to the fluidics' oscillation frequency, thus validating the ability of the actuator to influence the combustion process. As during the measurements without combustion, the oscillation frequency could be controlled by controlling the volume flow of the gas fed into the fluidics.

Next, the combustor was operated at conditions that featured a strong low-frequency combustion instability when no fuel was modulated. Applying fuel modulation resulted in attenuation of the combustion instability for some oscillation frequencies. The attenuation was highest when modulating the fuel flow in between the fundamental instability frequency and its subharmonic. Modulating the fuel flow at the subharmonic, however, resulted in an amplification of the instable mode.

The results obtained in this work show that the fluidic actuator in use allows for fuel modulation and hence combustion control without the need for complex and fast moving parts, thus ensuring a long actuator lifetime. This makes the fluidic oscillator highly appropriate for application in industrial gas turbines.

REFERENCES

[1] McManus, K. R., Poinsot, T., and Candel, S., "A review of active control of combustion instabilities," *Prog. Energy Combust. Sci.*, Vol. 19, pp. 1–29, 1993.

[2] Zinn, B. and Neumeier, Y., "An Overview of Active Control of Combustion Instabilities," *35th Aerospace Sciences Meeting & Exhibit*, Reno NV, Paper AIAA-1997-0461, 1997.

[3] Kiel, B. V., "Review of Advances in Combustion Control, Actuation, Sensing, Modeling and Related Technologies for Air Breathing Gas Turbines," *39th Aerospace Sciences Meeting and Exhibit*, Reno NV, Paper AIAA-2001-0481, 2001.

[4] Poinsot, T., Bourienne, F., Candel, S., Esposito, E., and Lang, W., "Suppression of Combustion Instabilities by Active Control," *J. Propulsion Power*, Vol. 5, No. 1, pp. 14–20, 1989.

[5] Candel, S. M., "Combustion instabilities coupled by pressure waves and their active control," *24th Symposium (International) on Combustion*, The Combustion Institute, pp. 1277–1296, 1992.

[6] Cohen, M. F., Rey, N. M., Jacobsen, C. A., and Anderson, T. J., "Active Control of Combustion Instability in a Liquid-Fueled Low-NOx Combustor," *ASME Turbo Expo '98, No. ASME Paper 98-GT-267*, Stockholm, Sweden, June 2-5 1998.

[7] Candel, S., "Combustion Dynamics and Control: Progress and Challenges," *Proceedings of the Combustion Institute*, The Combustion Institute, pp. 1–28, 2002.

[8] McManus, K. R., Magill, J. C., and Miller, M. F., "Combustion Instability Suppression in Liquid Fueled Combustors," *36th Aerospace Sciences Meeting*, AIAA Paper 98-0642, 1998.

[9] Paschereit, C. O. and Gutmark, E., "Active Control of Combustion Instabilities in Gas Turbine Burners," *ASME Paper GT2006-90186*, 2006.

[10] Yu, K. H., Wilson, K. J., and Schadow, K. C., "Liquid-Fueled Active Instability Suppression," *27th Symposium (International) on Combustion*, The Combustion Insitute, pp. 2039–2046, 1998.

[11] Dowling, A. P. and Morgans, A. S., "Feedback Control of Combustion Oscillations," *Annu. Rev. Fluid Mech.*, Vol. 37, 2005, pp. 151–82.

[12] Seume, J. R., Vortmeyer, N., Krause, W., Hermann, J., Hantschuk, C.-C., Zangl, P., Gleis, S., Vortmeyer, D., and Orthmann, A., "Application of Active Combustion Instability Control to a Heavy Duty Gas Turbine," *J. Eng. Gas Turbines and Power*, Vol. 120, 1998, pp. 721–726.

[13] Schuermans, B., "Modeling and control of thermoacoustic instabilities," Ph.D. thesis, Ecole Polytechnique Fédéral de Lausanne, 2003.

[14] Brundish, K. D., Nash, S., Wilson, C., Tippetts, J., "The Initial Design of a Fluidically Controlled Variable Geometry Fuel Injector for Gas Turbine Combustion Systems," *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Paper AIAA-1998-3908, 1998.

[15] Sun, F., Cohen, J. M., and Anderson, T. J., "Liquid Fuel Modulation by Fluidics Valve for Active Combustion Control," *Proc. of ASME Turbo Expo '02*, Amsterdam, Netherlands, Paper GT-2002-30607, 2002.

[16] Raman, G. and Raghu, S., "Cavity Resonance Suppression Using Miniature Fluidic Oscillators," *AIAA Journal*, Vol. 42, No. 12, pp. 2608–2612, December 2004.

[17] Morris, N. M., *An Introduction to Fluid Logic*, McGraw Hill, 1973.

[18] Kirshner, J. M. and Katz, S., *"Design Theory of Fluidic Components"*, Academic Press, New York, 1975.

[19] Viets, H., "Flip-Flop Jet Nozzle," *AIAA Journal*, Vol. 13, pp. 1375–1379, 1975.

[20] Guyot, D. and Paschereit, C. O., "Active Control of Combustion Instability Using Symmetric and Asymmetric Premix Fuel Modulation," *ASME Paper GT2007-27342*, 2007.

[21] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Acoustic and fuel modulation control for reduction of thermoacoustic instabilities," *Fourteenth International Symposium on Airbreathing Engines*, Florence, Italy, September 5–10 1999.

[22] Haber, L. C., Vandsburger, U., Saunders, W. R., and Khanna, V. K., "An Examination of the Relationship between Chemiluminescent Light Emission and Heat Release Rate under Non-adiabatic Conditions," *ASME Paper 2000-GT-0121*, 2000.

[23] Raman, G., "Using controlled unsteady fluid mass addition to enhance jet mixing," *AIAA Journal*, Vol. 35, No. 4, pp. 647-656, 1997.

[24] Raman, G., Packiarajan, S., Papadopoulos, G., Weissman, C. and Raghu, S., "Jet thrust vectoring using a miniature fluidic actuator," *The Aeronautical Journal*, Vol. 109, No. 1093, pp. 129-138, March 2005.

[25] Barooah, P., Anderson, T. J., Cohen, J. M., "Active combustion instability control with spinning valve actuator," *J. Eng. Gas Turbine Power – Trans. ASME* 125(4):925-32, 2003.

[26] Lubarsky, E., Shcherbik, D., Zinn, B. T., "Active control of instabilities in high-pressure combustor by non-coherent oscillatory fuel injection," *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Paper AIAA-2003-4519*, 2003.