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Suppression of Combustion Instability by Geometrical Design of the Bluff-Body Stabilizer

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Passive control methods were used to suppress combustion instability in a combustor with a bluff-body stabilizer. The instabilities in this combustor are excited by interaction between vortices shed downstream of the stabilizer and the combustion chamber acoustic modes. The passive control methodology was to change the geometrical design of the stabilizer in a manner that will disrupt the formation or reduce the coherence of the wake vortices, thus eliminating the source of the instability excitation. Two geometrical designs were tested and compared to the regular baseline disk stabilizer. The first was a corrugated stabilizer that promotes the shedding of longitudinal vortices from the stabilizer's base. These vortices induce azimuthal instability in the axisymmetric wake vortices and accelerates their breakdown. The second configuration was a multistep cone that was shown to enhance the production of small-scale turbulence in the flow. Both methods were effective in the suppression of the pressure oscillations and reduced significantly the range of unstable combustion without adversely affecting the lean and rich flammability limits. The optimal configuration was the multistepped cone stabilizer. The orientation of the stabilizers and the effect of central ventilations were studied as well as the instability mode characteristics.

Introduction

THE recirculation region downstream of a bluff body is used to stabilize premixed flames in combustors. The afterburner of an airplane engine and a ducted rocket combustor are common examples for this application. These combustors are limited in their operational envelope to certain flow rates and fuel-to-air ratios due to the occurrence of strong oscillations that restrict the range of stable combustion and produce high levels of acoustic emission. The source of this instability is associated with the vortex shedding behind the bluff body and its interaction with the duct acoustical resonating modes.[1–5] These results showed that the strong oscillations are associated with a standing quarter wave in the tube and that the shedding frequencies contribute to the oscillation in the transitional range of equivalence ratios. The differences between isothermal flows and the combustion tests were addressed in detail by Pita.[6]

Similar interaction between flow and combustion dynamics resulting in instabilities was identified in dump combustors.[7–9] Nonreacting tests in air and water flows, as well as combustion experiments in a diffusion flame and a dump combustor, provided insight into the generation process of large-scale structures in the combustor flow and their interaction with the combustion process.

It was shown that the flow structures, or vortices, are formed by interaction between the flow instabilities and the chamber acoustic resonance. When these vortices dominate the reacting flow, the combustion is confined initially to the circumference of their cores, and further downstream proceeds into their core, leading to periodic heat release, which may result in the driving of high-amplitude pressure oscillations. These oscillations are typical to the occurrence of combustion instabilities for certain operating conditions.

The basic understanding of the interaction between flow dynamics and the combustion process opened up the possibility for passive control of combustion-induced pressure oscillations.[10]

In a coaxial dump combustor, low-frequency pressure oscillations were suppressed using combined shear-flow and fuel-injection control. A multistep dump[11,12] was used to eliminate the periodic heat release due to vortex combustion by generating multiple sources of turbulence production. A similar geometry was used in a gas-generator combustor resulting in flame stabilization and enhanced energy release. Another passive-control method is based on the generation of axial vorticity[13,14] that enhanced turbulence production and increased mixing rate.

In the present article these passive control methods are extended to bluff-body flameholder configurations. The concepts of multistepped geometry and the axial vorticity generators were implemented in the flameholder design. The geometries that were developed at the Naval Weapons Center, California, were tested in a bluff-body stabilized combustor at the Instituto Superior Tecnico, Lisbon, Portugal. The wall static-pressure fluctuations were measured and used to characterize the domain of unstable combustion as a function of the mixture velocity and equivalence ratio for different bluff-body geometries and compared for the standard disc stabilizer. For the disc the flowfield was measured in isothermal and combustion tests, as well as the temperature distribution.[15]

Experimental Apparatus

Figure 1 shows the combustion rig located at IST, Lisbon, Portugal. It is constructed of a stainless steel tube of 71 mm i.d. with a variable length. The fixed portion in the present

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Table 1 Flameholder configurations

Configuration code	Flameholder geometry	Center ventilation	
		Open	Close
A	Disc	——	A2
B	Short corrugations facing downstream	B1	B2
C	Short corrugations facing upstream	C1	C2
D	Long corrugations facing downstream	D1	D2
E	Long corrugations facing upstream	E1	E2
F	Stepped cone, base facing upstream	F1	F2
G	Stepped cone, base facing downstream	G1	G2

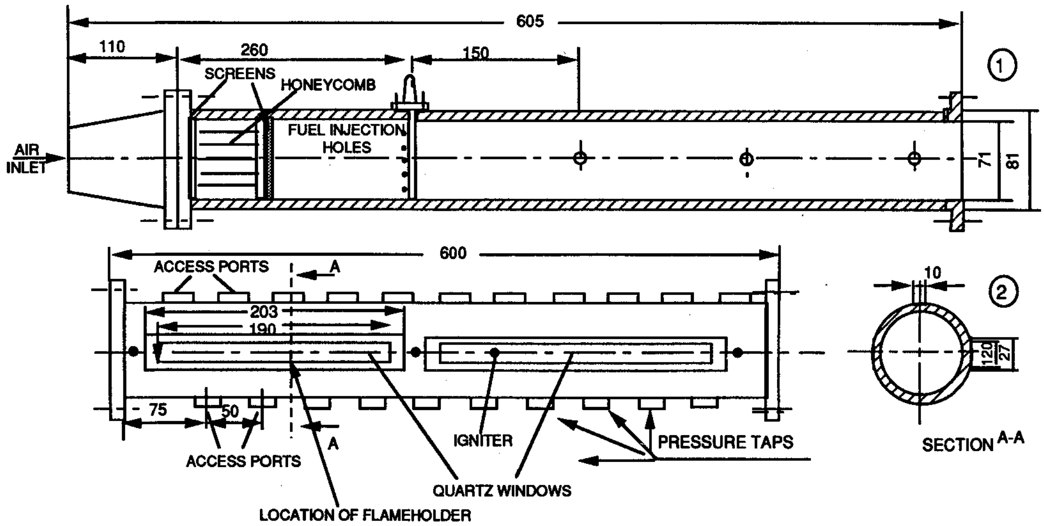

Fig. 1 Combustion rig (all dimensions in mm).

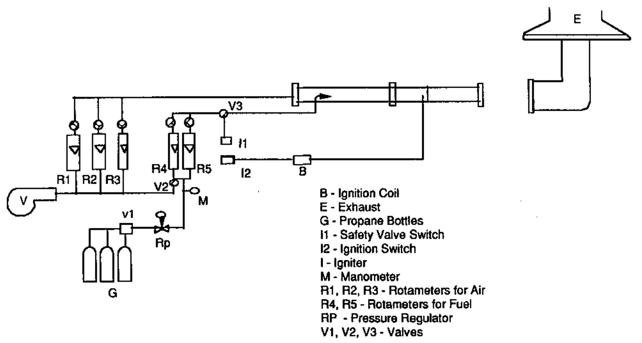

Fig. 2 General scheme of the rig.

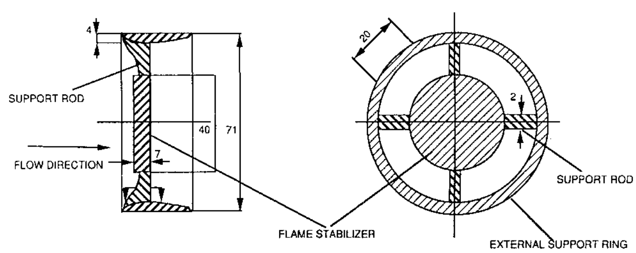

Fig. 3 Flame stabilizers support (all dimensions in mm).

test is 695 mm long attached to a 600- or 1000-mm-long combustor. At the inlet to the cold tube, screens and honeycomb are installed to straighten the flow coming from the air supply through a tube 1805 mm long. The fuel, propane, is injected normal to the flow at a distance of 200 mm from the inlet through a 7-mm-diam tube, through five holes, into the upstream direction to ensure good mixing. The working section has two sets of access ports, with a pitch of 50 mm. The ports can be used for pressure measurements, ionization probes, and thermocouples. It is also equipped with three quartz windows that give optical access to the flame downstream of the flame stabilizer. A fourth window is used to support the ignition spark plug and the radial traversing mechanism.

Figure 2 depicts the general scheme of the rig. Air is supplied by high-pressure centrifugal fan through two rotameters (R1, R2) with a maximum flow rate of 80 g/s and one rotameter (R3) with a maximum capacity of 4 g/s. The fuel is supplied from eight bottles, 45 kg each. The fuel rotameters (R4, R5) have a maximum capacity of 4 and 0.6 g/s, respectively. The power released in the combustion chamber is in the range 40–100 kW. Ignition is obtained by a spark plug operated manually by switch (I2).

The flame stabilizers are supported in the center of the duct by four 2-mm-thick rods that extended from an external ring support (Fig. 3). The ring has an o.d. slightly less than 71 mm to fit inside the combustor pipe. It has a convex cross section with a maximum thickness of 3 mm to minimize disturbance to the flow. All the flameholders have a diameter of d = 40 mm, with a blockage ratio of 39%, including the support.

The stabilizer can be located in any position along the combustor. In the present tests, the stabilizer is mounted at 360 or 760 mm from the combustor exit, with the upstream length constant (l = 2740 mm).

Table 1 describes the flameholder configurations tested. The different geometries are shown in Fig. 4. The disc flameholder (A) was 5 mm thick. Configuration B had a circular cross section in the upstream side and a corrugated base in the downstream side, with eightfold symmetry. The i.d. was 20 mm and the stabilizer length 20 mm. Configuration C had an equal geometry, but the circular cross section was in the downstream side and the corrugated base in the upstream

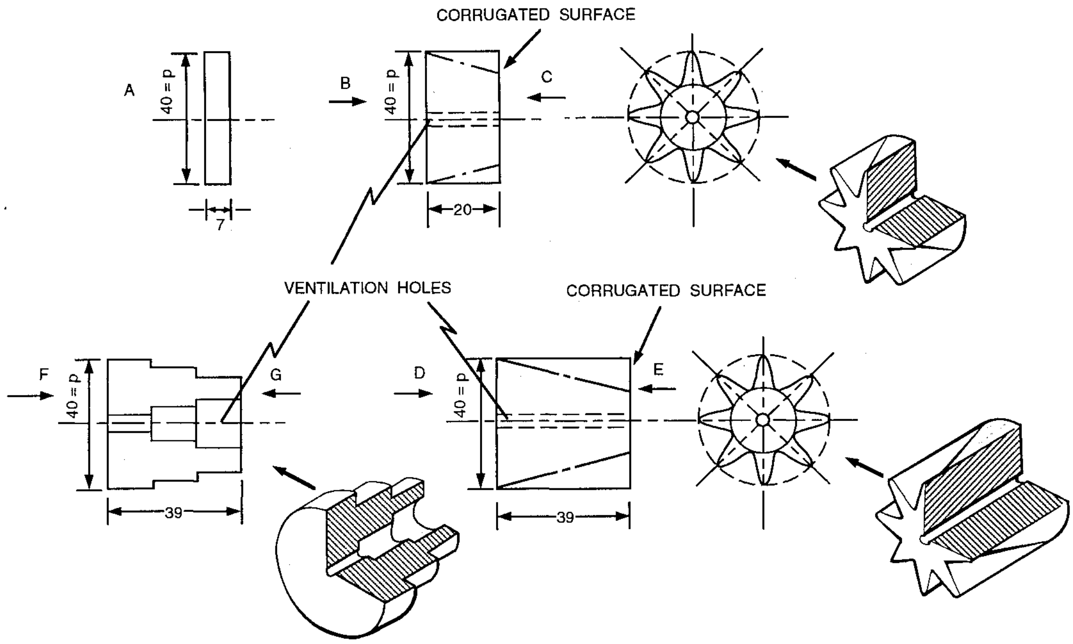

Fig. 4 Flameholder configurations. Arrows indicate flow direction and the configuration code in Table 1.

side. Configurations D and E were identical to configurations B and C, respectively, except for the length that was double (40 mm). Configuration F was a cone with the base facing upstream; the cone had multisteps in the external and in the internal surface. Configuration G was geometrically identical to configuration F, but the cone base was pointing downstream.

To measure static pressure fluctuations, a Kistler pressure transducer model 211B5 was used, with an amplifier model 5108. The maximum frequency response was 5 kHz. The measurements were performed upstream of the stabilizer in the cold pipe, at a distance from the flameholder ranging from 0.3 to 2.25 m, to avoid exposure of the Kistler probe to the high temperatures downstream of the flameholder.

Axial velocity and turbulence level measurements were performed using laser Doppler velocimeter (LDV) downstream a 32-mm disc. The one component LDV system included two Bragg cells and a counter.

The data acquisition system used was a data translation model 2824-PGL analog-to-digital converter with a maximum sampling rate of 50,000 sample/s and 12-bit resolution. A sampling rate of 5000 samples/s was used in most of the pressure measurements.

Results

Flowfield in Disc-Stabilized Tests

Mean velocity and turbulence flowfields were measured for isothermal and combustion conditions using LDV downstream of a disc stabilizer with 32 mm diam. Axial mean velocity and turbulence intensity downstream the flameholder in an isothermal test are shown in Fig. 5. The airflow was 25.8 g/s and the axial mean velocity in the disc area was 8.9 m/s.

The recirculation zone length was 2.32 times the disc diameter, as determined from the negative velocities. At this range the turbulence level is increased, reaching a maximum level of 0.2 relative to the mean velocity. Downstream of the recirculation zone, the turbulence decays. Mean and turbulent profiles of the isothermal tests are depicted in Figs. 6a and 6b, respectively, inside and downstream of the recirculation zone. The velocity profiles become uniform at $x/D > 3.75$. Highest production of turbulence is measured in the separated wake shear layer at $X = 0.93D$; farther downstream the turbulence decays.

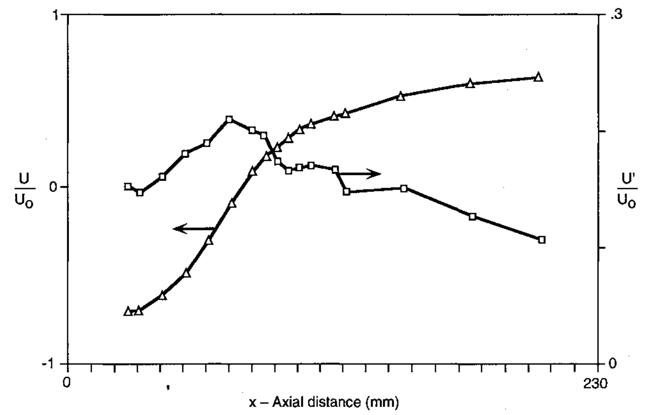

Fig. 5 Axial mean velocity and turbulence intensity in the centerline downstream of a disc, isothermal flow.

The same tests were repeated with combustion, in the stable lean combustion zone. Mean velocity and turbulence intensity variation along the combustor axis are shown in Fig. 7. The recirculation zone length becomes shorter, $L/D = 1.37$, relative to the isothermal tests, and the mean velocity along the axis is significantly higher ($U/U_0 > 2$ relative to 0.8). The turbulence intensity remained constant at a level of $u/U_0 = 0.18$. There is no decay of turbulence downstream of the end of the recirculation zone.

The velocity profiles in the combustion tests (Fig. 8a) indicate that the wake is not fully mixed, even at $x/D > 6.56$. However, due to the decreased length of the recirculation zone, the turbulence production in the shear layer is diminished for $x/D > 2.5$ (Fig. 8b) and its peak level at the shear layer ($x/D = 0.93$) is lower relative to the isothermal case.

Flammability Limits

The flammability limits, equivalence ratio where flame extinction occurs, for the different flameholder configurations (listed in Table 1) are shown in Fig. 9 as a function of the mean axial velocity in the flameholder area. The flammability limits do not change for the various flameholders studied. This result confirms previous observations[16] that the flammability limits relate to the stabilizer diameter. The lean flammability limit is essentially constant, equivalence ratio 0.5–

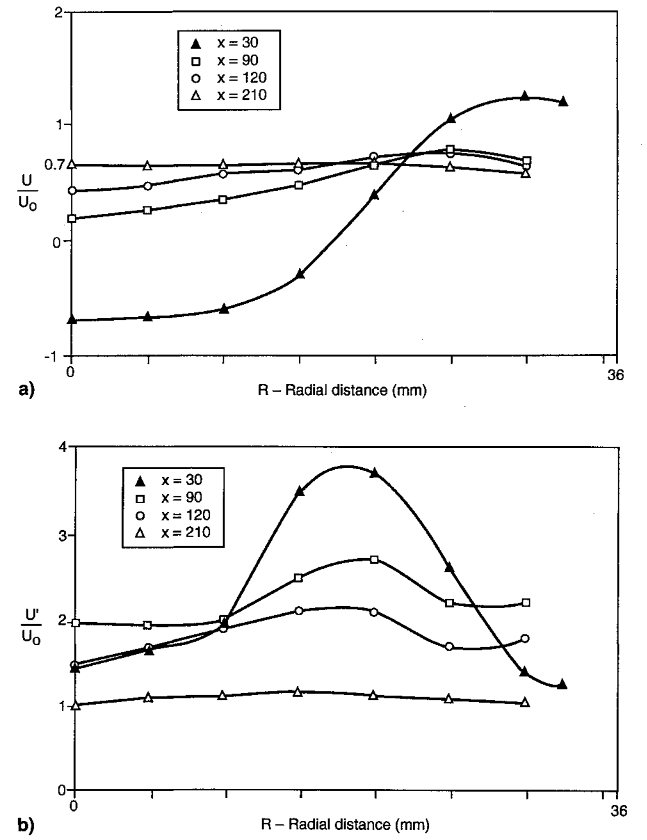

Fig. 6 Radial profiles in isothermal tests (x = 30, 90, 120, and 210 mm): a) axial mean velocity and b) turbulence intensity.

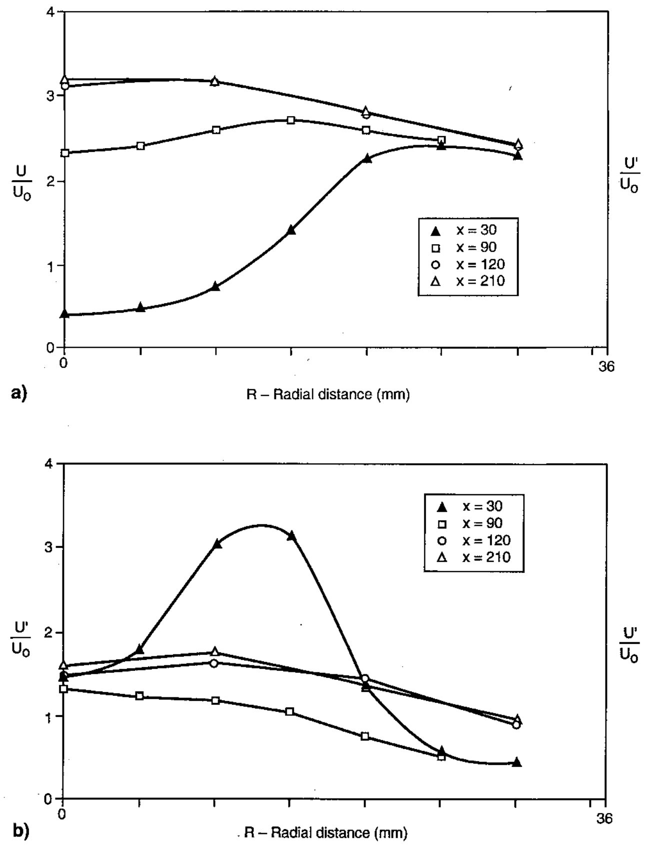

Fig. 8 Radial profiles in combustion flow (x = 30, 90, 120, and 210 mm): a) axial mean velocity and b) turbulence intensity.

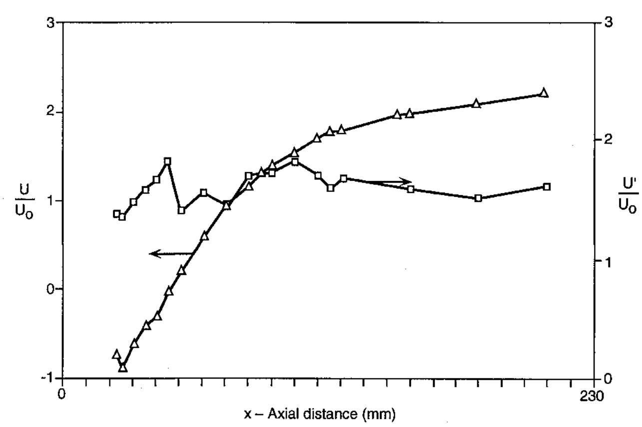

Fig. 7 Axial mean velocity and turbulence intensity in the centerline downstream of a disc, combustion flow.

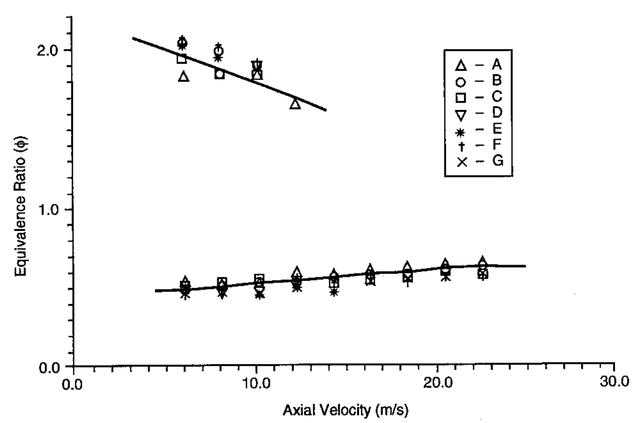

Fig. 9 Flammability limits from the different flameholders hot tube length—360 mm (symbols codes indicated in Table 1).

0.6, and the rich flammability limit has a decay with the increase of the axial velocity. Due to safety reasons it was not possible to measure the rich limits for higher velocities.

Wall Static Pressure Measurements

Wall static pressure measurements were made along the cold tube with the flame stabilized by flameholder B2 and a hot length of 360 mm. The mixture axial mean velocity in the stabilizer area was 9.03 m/s and the equivalence ratio 1.26. The rms of pressure fluctuations for these unstable combustion conditions are plotted in Fig. 10. A standing wave, which corresponds to the second harmonic of the acoustic quarter wave, is detected with a pressure node in the stabilizer zone. The main frequency of the pressure oscillations spectrum measured with an FFT software was 107 Hz. This same frequency was present in the wall static pressure power spectrum measured with a 760 mm hot length.

Wall static pressure measurements, for the remainder of the tests, were made with the pressure probe located 0.76D upstream of the stabilizer, as indicated in Fig. 10, in order to obtain the rms of the pressure fluctuations for the different flameholders listed in Table 1, and for two different hot pipe lengths in the stable and unstable flame zone.

The sound pressure level was measured in "decibel" defined as:

Sound pressure level = Lp = 20 log(p/p ref) dB
p ref = 2 × 10 E-5 N/m^2

By visual and acoustic observation of the flame, unstable combustion was associated with wall pressure rms levels greater than 140 dB.

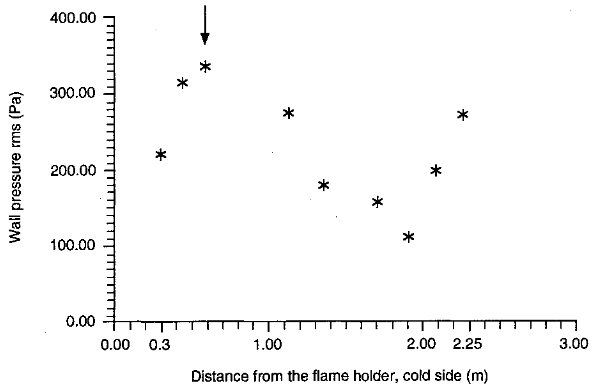

Fig. 10 Wall pressure rms measured along the cold tube.

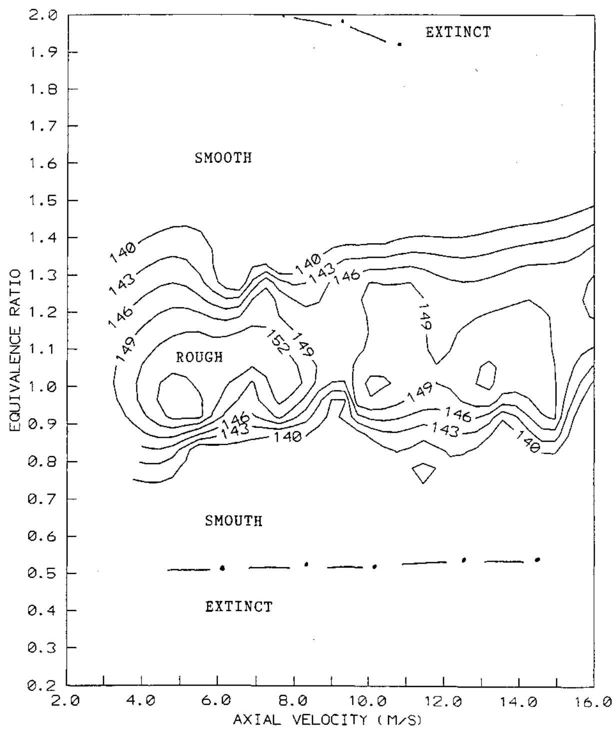

Fig. 11 Disc A2. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

Stability Domain

The stability domain of the flame for the different flameholder geometries, listed in Table 1, and for two different hot tube lengths, were determined by measuring the wall pressure fluctuations rms.

It was observed that in order to measure the flame stability domain it was necessary to let the temperatures inside the combustion chamber rise to the stationary values. In the first minutes of the tests, when the stabilizer and combustion chamber walls were still cold, no unstable combustion was observed; only after several minutes, when wall temperatures were higher, did combustion become unstable. This phenomenon was related to the effect of the stabilizer and wall temperatures on the flame location. When the combustion chamber got hotter, the flame moved upstream closer to the stabilizer, thus reaching the optimal location for the excitation of the chamber acoustic resonance.

Measurement Made with a Short Hot Tube, Length of 360 mm

Figure 11 shows the wall pressure rms contours as a function of the mixture velocity in the stabilizer area and the mixture equivalence ratio when flameholder A2 (disc) was used. The lean limit of unstable combustion is independent of the axial velocity at a level of $\phi = 0.85$, and the rich limit slightly increases with velocity, from 1.25 to 1.5. The pressure fluctuations reach a maximum level near the stoichiometric conditions for the lower mixture velocities. This maximum shifts to the rich zone as the flow velocity increases.

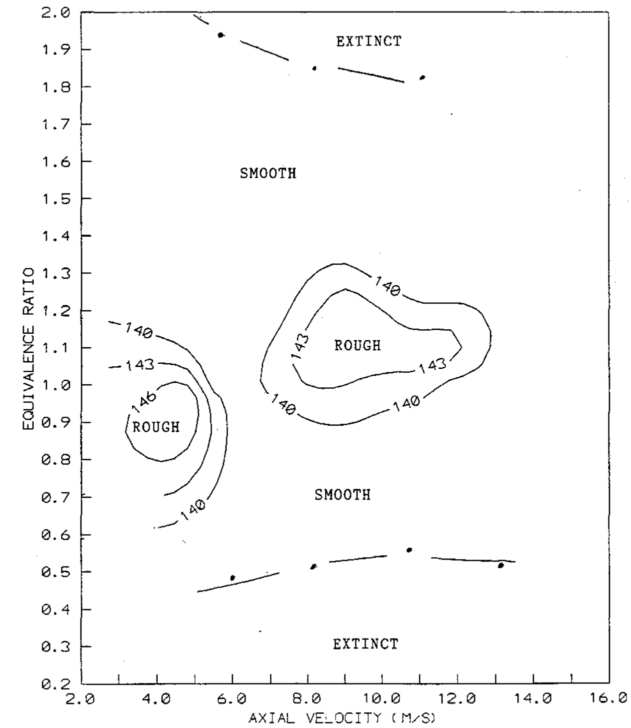

Fig. 12 Short corrugations facing downstream, ventilation open—B1. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

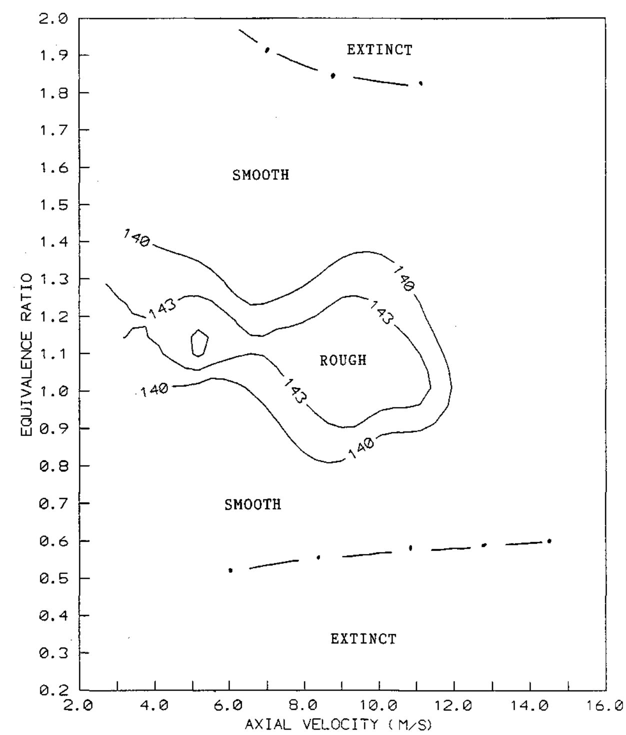

Fig. 13 Short corrugations facing downstream, center ventilation closed—B2. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

Stabilizer B (short corrugations facing downstream) was used with center ventilation opened, B1, Fig. 12, and center ventilation closed, B2 (Fig. 13). There are no significant differences between the rms of pressure fluctuations measured with the center ventilation open or closed. This conclusion was observed for all the other stabilizers used.

Contrary to the results for the disc, for stabilizer B, unstable combustion was not measured for velocities higher than 12 m/s. For the lower mixture velocities, $U < 12$ m/s, the equivalence ratio ranges where unstable combustion occurs is somewhat smaller than those for the disc, as well as the amplitude of the pressure fluctuations.

When the stabilizer with the short corrugations is facing upstream (configuration C2), the velocity at which the unstable combustion disappears is lower than $U = 9$ m/s (Fig. 14), and the range of equivalence ratios at which unstable combustion occurs is displaced towards the lean region, 0.8–1.2. The rms of the pressure fluctuations in the unstable combination region has a similar value as for stabilizer B.

The stabilizer with the long corrugation facing upstream, configuration E2, has an unstable combustion domain similar to stabilizer B (Fig. 15). The pressure fluctuations rms are below 140 dB for mixture velocities higher than 12 m/s. At velocities lower than 12 m/s, the range of equivalence ratio where the combustion becomes unstable is 0.8–1.3.

The stepped cone, base facing upstream, F1, has a stability domain equal to stabilizer E2 (Fig. 16). Tests made with stabilizers E1 and F2 showed that the stability domain is not different from that obtained with stabilizers E2 and F1. Both stabilizers E2 and F1 present in the unstable combustion domain values of the pressure fluctuations rms higher than stabilizers B1, B2, and C2 and equal to the disc rms values.

Figure 17 shows the reduced unstable combustion region measured for stabilizer G1. For $U > 10$ m/s, the combustion becomes stable inside the flammability limits and for velocities lower than 7 or 8 m/s, depending on the mixture equivalence ratio, the pressure fluctuations rms is about 135 dB. The disappearing of the combustion oscillations at low velocities is accompanied with a shift of the flameholding location to the upstream part of the flameholder.

Measurements Made with a Long Hot Tube, Length of 760 mm

The amplitude of the combustion instability was high for all the flameholders at this length. Representative measurements for these conditions are shown for stabilizer C2. Figure 18 shows the stability and flammability domain of the short corrugations facing upstream, C2, with a long hot tube (LH

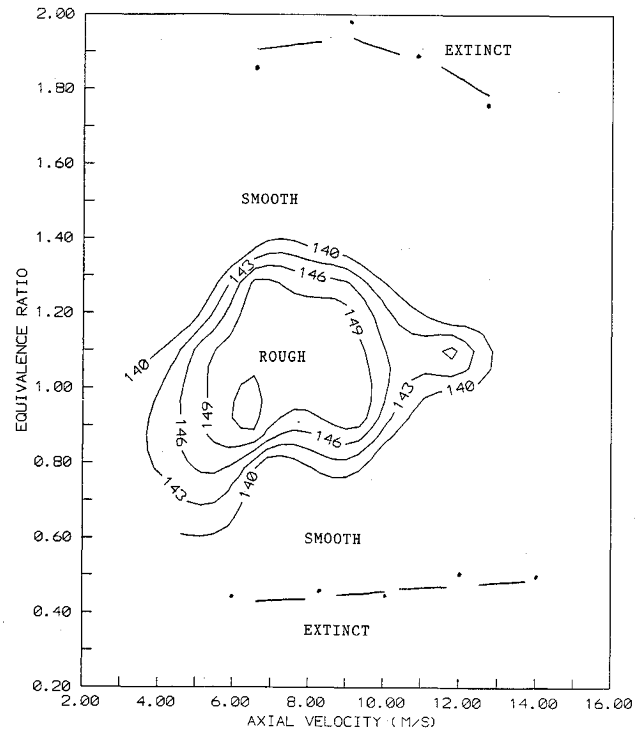

Fig. 15 Long corrugations facing upstream, ventilation closed—E2. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

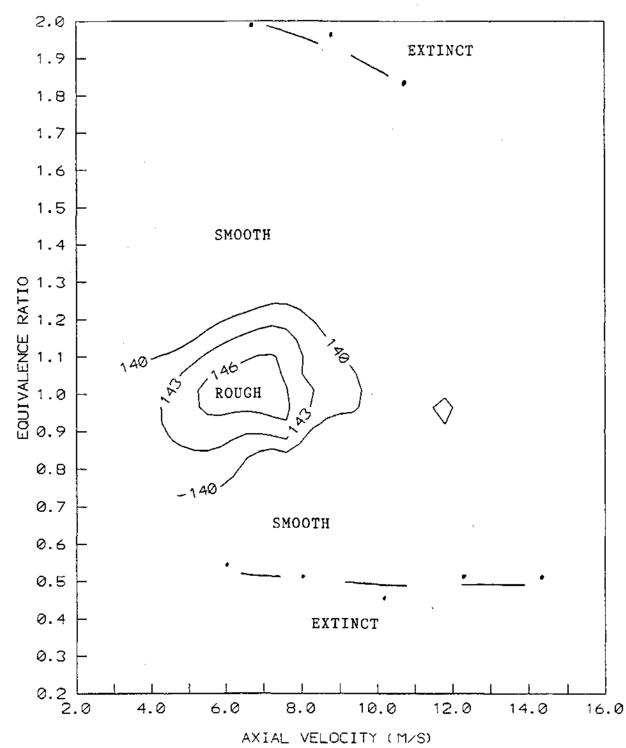

Fig. 14 Short corrugations facing upstream, center ventilation open—C1. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

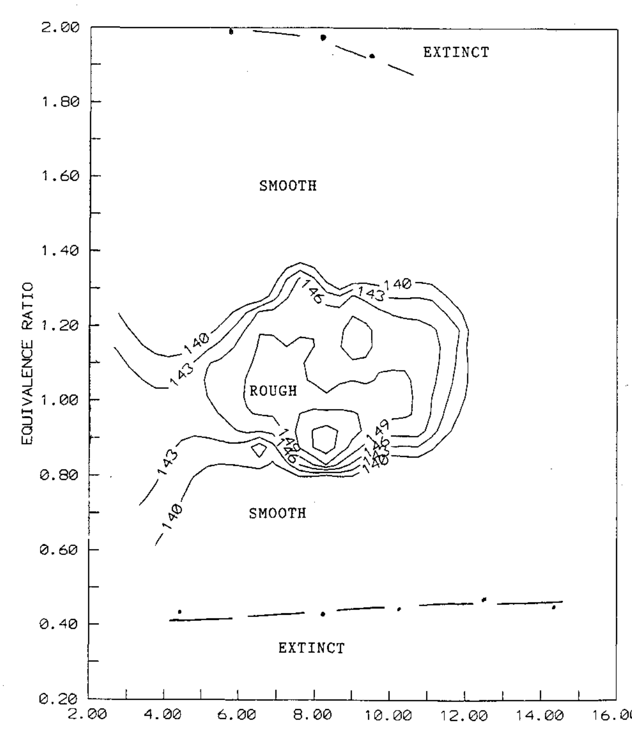

Fig. 16 Stepped cone facing upstream, ventilation open—F1. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

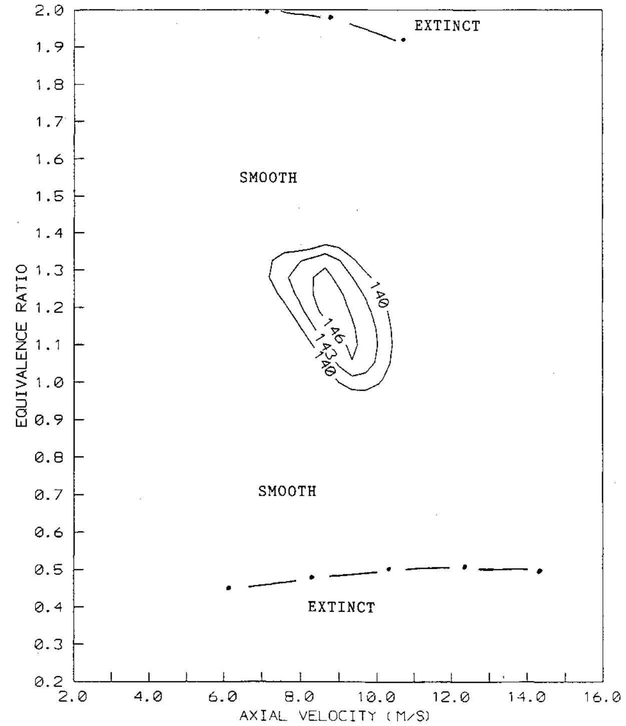

Fig. 17 Stepped cone facing downstream, ventilation open—G1. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

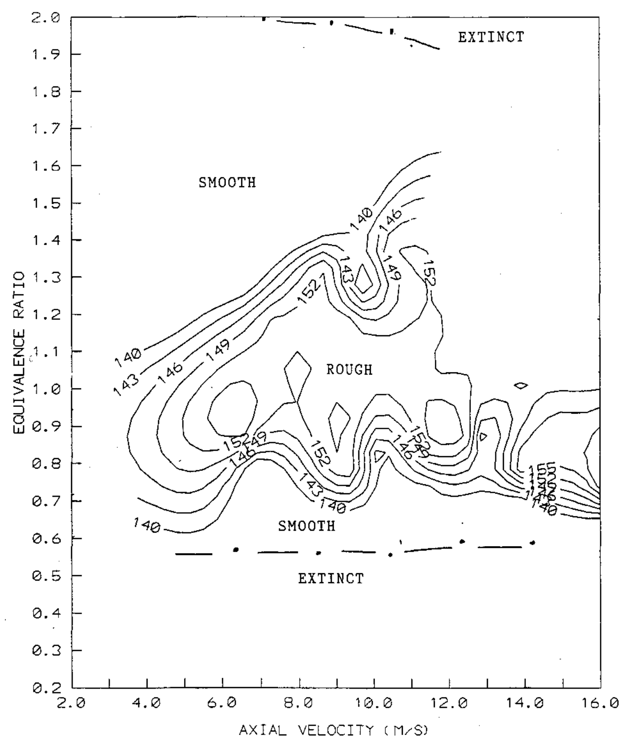

Fig. 18 Short corrugations facing upstream, ventilation closed—C2. Flammability limits and contours of the wall pressure rms indicating the unstable domain.

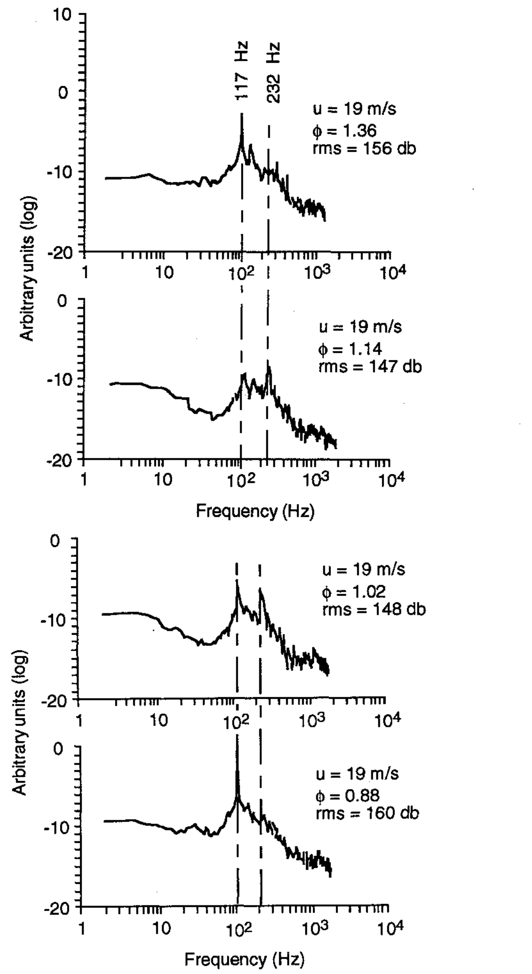

Fig. 19 Wall pressure power spectrum long hot tube, L_H = 760 mm stabilizer C2.

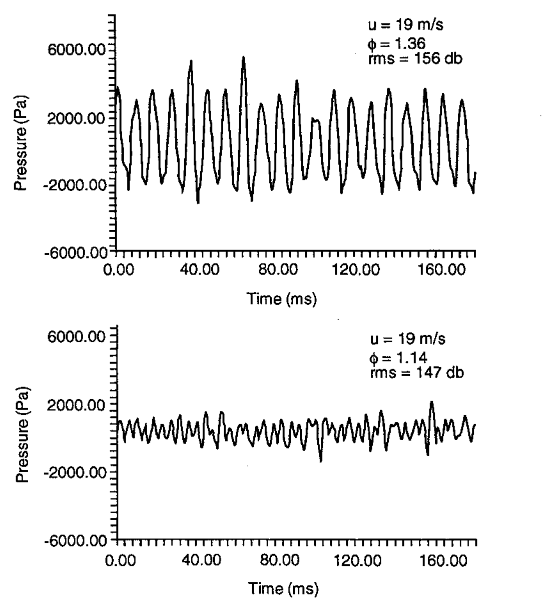

Fig. 20 Wall pressure time traces.

= 760 mm). The flammability limits did not change relative to the values measured with the same stabilizer using the short hot tube. The stability domain, however, has changed significantly. The unstable combustion extends to the entire velocity range tested. The lean limit is almost constant, at an equivalence ratio of 0.7. The rich limit increases with the increase in velocity. For velocities higher than 11 m/s the rich limit is difficult to determine as the flame becomes very unstable and occasionally blows out.

The intensity of the pressure fluctuations is higher than with the short hot tube using the same stabilizer. At low velocities, $U < 10$ m/s, the maximum of rms values is at the stoichiometric region. For increased velocity there are two maxima at the same velocity, one in the lean and one in the rich region. This change in rms amplitude is concurrent with a change in the instability frequency detected in the wall pressure power spectrum (Fig. 19). In the lean region (ϕ = 0.88) the single mode instability is at a frequency of 117 Hz with an overall pressure fluctuations intensity of 160 dB. Near the stoichiometric ratio (ϕ = 1.02 and 1.14), the pressure fluctuation level decreases by 12–13 dB and a bimodal instability appears at 117 Hz and its first harmonic. At richer mixture (ϕ = 1.36) the pressure fluctuations level increases back to nearly the lean level and the harmonic component disappears again. Figure 20 shows the pressure traces recorded for equivalence ratios of 1.36 and 1.14 and an axial velocity of 19 m/s. The frequencies detected were 117 Hz for ϕ = 1.36 and 0.88, and 117 and 232 Hz for ϕ = 1.14 and 1.02, the emergence of the harmonic resulted in a reduction in the overall pressure fluctuations amplitude.

Summary and Conclusions

The range of unstable combustion was reduced significantly by varying the bluff-body stabilizer geometry, relative to a standard circular bluff-body stabilizer. The instability that occurs using the latter stabilizer is associated with the interaction of vortices shed behind this stabilizer and the acoustic resonance modes of the combustor. The passive control methods studied in this article are based on the idea that geometrical changes of the stabilizer affect the flowfield in such a way that the formation of the wake vortices are disrupted and the excitation source of the acoustic modes is abated. The corrugated stabilizer, facing downstream or upstream, was designed to generate axial vortices in the flow. These vortices induce the formation of azimuthal (circumferential) instabilities superimposed on the axisymmetric vortices. These instabilities are amplified and eventually lead to the breakdown of the vortices into small-scale turbulence. The multiple-steps on the stabilizer promote the production of small-scale turbulence in the wake flow, thus reducing the coherence of the wake vortices. The experiments described in this article show that both methods were effective in reducing the intensity of the unstable combustion region, while the flammability limits remained unchanged.

The most effective configuration, which shrank the unstable region to a minimal range, was the multistepped cone facing downstream. In the long combustor experiments, the oscillation level was extremely high (>165 dB), and the only stabilizer that reduced the oscillations below 160 dB was the one with the short corrugations facing upstream. At these conditions, a mode switch in the instability was observed as the equivalence ratio was changed. At stoichiometric conditions, another higher harmonic of the quarter wave frequency appeared, resulting in a bimodal instability. For rich or lean conditions, only one harmonic of the quarter wave was present. This was the same frequency that dominated the short combustor instability.

In all the stabilizer configurations tested, there was not a significant difference between stabilizers with and without central ventilation.

Velocity measurements were made in an isothermal flow and in a combustion flow in the region downstream of a disc stabilizer. The length of the recirculation zone becomes smaller in the reacting flow.

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