Suppression of Oscillations in Confined Disk-Stabilized Flames

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Combustion oscillations in confined axisymmetric flames stabilized behind a bluff body in a uniform duct are compared for ducts with acoustically open and closed upstream ends, with the upstream duct length as a variable. The influence of bends in the upstream duct is examined and shown to be small. The use of a strategically located orifice in the upstream duct is shown to lead to the suppression of oscillations in ducts with an acoustically closed upstream end, and the same principle has been applied successfully in ducts with an acoustically open upstream end. The influences of duct diameter, upstream length, orifice diameter, and location are quantified. It is also shown that smooth convergent-divergent nozzles can be used in place of orifices to suppress combustion oscillations.

Nomenclature

D = diameter of duct (Fig. 1)
D_1 = diameter of orifice immediately upstream of flameholder (Fig. 1)
D_2 = diameter of orifice at upstream end of acoustically open duct (Fig. 1)
f = frequency
f_1 = half-wave frequency of length between orifice and flameholder
f_2 = quarter-wave frequency of length between orifice and flameholder
L = downstream length of duct (Fig. 1)
U_0 = mean flow velocity upstream of flameholder
Re = Reynolds number = U_0D/ν
X = upstream length of duct (Fig. 1)
X_1 = location of orifice diameter D_1
λ = wavelength
ν = kinematic viscosity of air fuel mixture
ϕ = equivalence ratio of air fuel mixture

Subscripts

$\lambda/4$ = quarter-wave (frequency of upstream duct length)
$\lambda/2$ = half-wave
$3\lambda/4$ = three-quarter wave
λ = full-wave

Introduction

THE main purpose of this investigation of oscillations in combusting flow is to devise ways of avoiding or suppressing them. Axisymmetric confined premixed flames, stabilized behind bluff bodies with modest blockage ratio, were extensively investigated in Refs. 1-3, and flammability and stability limits were established for a wide range of duct geometries with an upstream impedance identified as an impermeable wall. The duct length downstream of the flameholder was found to be important only insofar as it was adequate to confine the flame so as to sustain the instability. In ducts of uniform diameter and composite ducts with the overall variation in upstream duct diameter not exceeding two, oscillations were associated with acoustic quarter-waves in the cold length upstream of the flameholder. Reference 3 showed that oscillations in ducts with long upstream lengths could be suppressed by correctly locating an orifice of suitable diameter in the upstream section. The suppression was caused by the interaction of a half-wave frequency in the length between the acoustically closed end and the orifice and a quarter-wave frequency in the length between the orifice and the flameholder, and was effective for orifice locations except those close to one-third or the upstream length from the flameholder, with which strong oscillations associated with a three-quarter wave frequency were encountered.

The present results quantify the influence of duct length and diameter and of upstream impedances such as bends, orifices, and nozzles that may be used in suppressing oscillations, and include the consideration of uniform ducts with open upstream ends. The extent to which suppression of oscillations can be achieved in ducts with acoustically closed and open upstream ends is examined for fully turbulent flows with incompressible upstream conditions. Extrapolation of the results to higher flow rates and different burner geometries should be made with care.

The following section describes the flow configurations and measurement techniques and is followed by a presentation and discussion of the results. The final section summarizes the more important conclusions.

Flow Configurations and Instrumentation

The flow configurations are shown in Fig. 1 along with their essential dimensions. In configurations A-D, the upstream end of the duct was connected to a swirl register, where the air supply was mixed with natural gas (94% CH_4). The reflection coefficient at this end was estimated at 0.94 and ensured that the duct was, in effect, acoustically closed. Swirl was subsequently removed by a length of honeycomb placed a short distance downstream of the swirl register. The flameholder, a 25% blockage disk, was supported on an upstream sting held in position by two sets of radial pylons and located downstream of a wire-mesh screen serving as a flame arrester. In configuration E, an open upstream end was simulated by a plenum chamber separating the duct length upstream of the flame-holding disk and the short duct length leading from the swirl register.

Measurements in combusting flow included volume flow rates of air and fuel obtained with calibrated rotameters. The flow measurements were precise to within 1% in the upstream Reynolds number and 3% in the mixture equivalence ratio. Free field sound intensity at a location 20 duct diameters from the duct exit and along a normal to the duct axis and static pressure fluctuations along the duct wall were obtained to a precision of 0.1 dB using a condenser microphone whose output was processed in a digital fast Fourier transform analyzer to give power spectra.

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Results

Uniform Straight Duct with an Acoustically Closed End

The measurements were carried out mainly in 40-mm ducts rather than the 80-mm ducts of earlier work, in view of the very high sound intensities obtained in ducts with the larger diameter and of the large number of runs and their duration. Figure 2 shows the variation of flammability and stability limits along with sound intensity and the dominant frequency at stoichiometry with the upstream duct length varying between 8 and 33 diameters and an upstream Reynolds number of 37,000. With upstream lengths less than 7 diameters, combustion could hardly be achieved at the stoichiometric condition. With larger upstream lengths and in the range of equivalence ratios that gave rise to unstable combustion, the main frequency of oscillations, referred to hereafter as the dominant frequency, is in the range between 100 and 210 Hz, with oscillations associated entirely with the quarter-wave frequency for lengths less than 25 diameters. Oscillations associated with the next harmonic (three-quarter-wave) frequency are first observed at a length of 25 diameters, where the three-quarter-wave frequency matches the maximum frequency of 210 Hz. The results are consistent with those of Ref. 3 for the 80-mm duct with frequencies between 70 and 170 Hz and the higher harmonic first observed at 15 diameters, where the three-quarter-wave frequency is about 170 Hz. The sound intensity at stoichiometry for the 40-mm duct is on average 10 dB less than that reported in Ref. 3 for the 80-mm duct under comparable flow conditions.

Uniform Straight Duct with Open Upstream End

The validity of simulating an open upstream end using a plenum chamber of a sectional diameter several times larger than that of the duct was checked by measuring the wall static pressure fluctuation along the upstream duct length, with the length of the plenum chamber varied by a factor of two and the length of the ducting leading to it by a similar ratio. Tests were also carried out with absorbent material on the walls of the plenum chamber, and this had no effect on the combustion characteristics for 40- and 51-mm ducts.

Figure 3 shows the variation of flammability and stability limits along with sound intensity and the dominant frequency at stoichiometry for a 40-mm duct with the upstream length varying between 6 and 40 diameters at an upstream Reynolds number of 37,000. The range of values for the dominant frequency is similar to that for the duct with an acoustically closed end. Rough combustion is entirely associated with acoustic half-waves for upstream duct lengths between 16 and 34 diameters, and oscillations associated with the next harmonic (full-wave) frequency are first observed at 35 diameters, where the full-wave frequency matches the maximum value of the dominant frequency. Rough combustion was not observed at upstream lengths between 6 and 16 diameters. Although combustion was smooth across the flammability limits for upstream lenghts less than 5 diameters, the flame could not be stabilized at Reynolds numbers greater than 25,000. The absence of rough combustion at upstream lengths less than 16 diameters is attributed to the fact that the relevant half-wave frequency is much higher than the maximum value of the dominant frequency.

The dominant frequency for the 51-mm duct was in the range between 90 and 190 Hz, with combustion associated with half-waves only for upstream duct lengths between 15 and 32 diameters and a full-wave frequency observed in lengths exceeding 32 diameters.

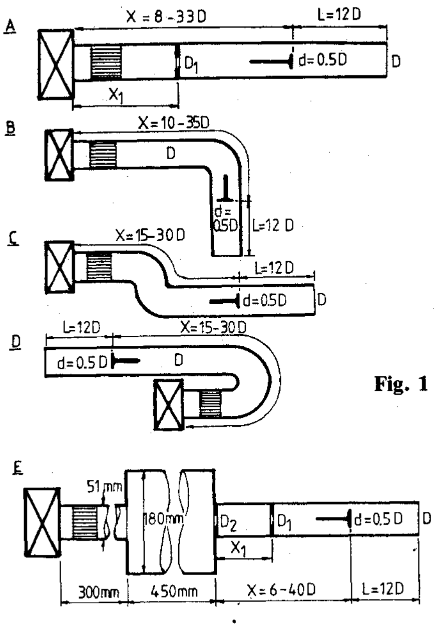

Fig. 1 Flow configurations.

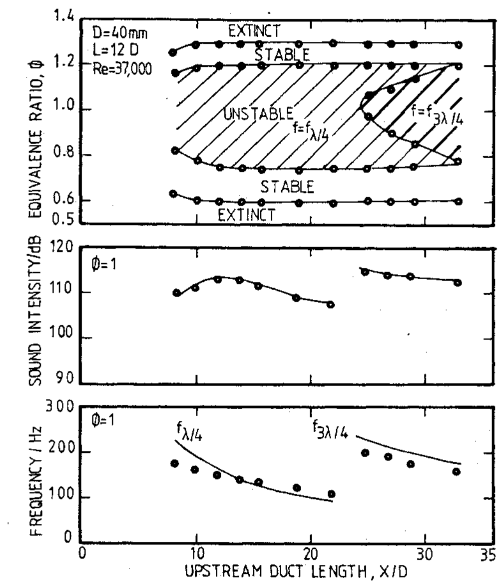

Fig. 2 Flammability and stability limits, sound intensity, and frequency (acoustically closed upstream end).

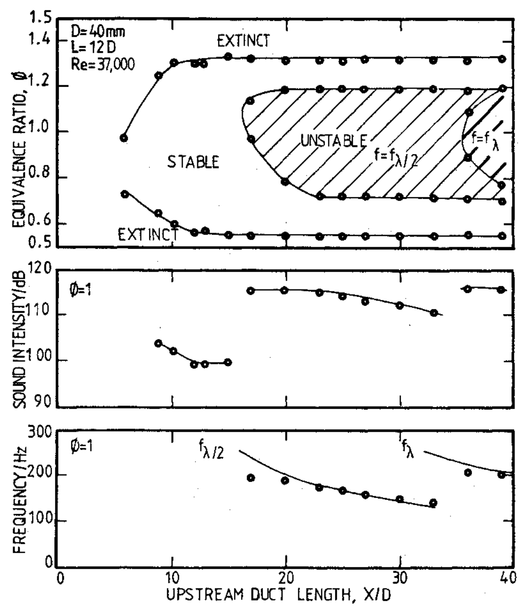

Fig. 3 Flammability and stability limits, sound intensity, and frequency (acoustically open upstream end).

Influence of Bends

Sharp bends in pipes are associated with high acoustic impedance, and locating a bend near an acoustic pressure node could attenuate oscillations and augment them near an antinode. The effect of curvature and location of bends was examined using elbow, *U*, and *S* bends of centerline radii of 0.5, 1.0, and 2.0 of the duct diameter *D* in a 40-mm duct at Reynolds numbers between 20,000 and 45,000. The two larger radii bends were ineffective, and the bend of radius 0.5 *D* did not have a significant effect on the frequency of oscillations, except with upstream lengths between 23 and 26 diameters and with the location of the bend one-third of the upstream length from the acoustically closed end; this combination made the burner less prone to oscillations in the higher harmonic (three-quarter-wave) frequency. Sound intensities were 7 dB less for oscillations associated with the quarter-wave frequency than for the higher harmonic. Location of this bend one-third of the upstream length from the flameholder made it more prone to oscillations in the higher harmonic frequency. The sensitivity of the oscillations to the location of the bend for this range of upstream lengths is associated with the transition to the higher harmonic frequency in straight ducts, which was observed at an upstream length of 25 diameters. With other upstream lengths, locating the bend close to an acoustic node resulted in reductions of the order of 1 dB in sound intensity, but the frequency of oscillations was not affected by the presence of the bend. It appears that the impedance of bends is inadequate on its own to be significant in the suppression of oscillations.

Suppression of Oscillations in Ducts with an Acoustically Closed End

The acoustic impedance of orifices increases with decreasing orifice diameter. Orifices of large diameter offer little acoustic impedance and are not likely to affect the acoustic characteristics of the duct. Orifices of very small diameter, on the other hand, have a high acoustic impedance and could act as pressure antinodes. With orifices of diameters between 0.35 and 0.6 *D* located between the acoustically closed end and the flameholder, combustion oscillations are associated with a quarter-wave frequency in the duct section between the orifice and the flameholder. Interaction between this frequency and the half-wave frequency in the duct section immediately upstream of it results in a suppression of oscillations. With orifice diameters smaller than 0.35 *D*, interaction between the frequencies appeared to be negligible.

Figure 4a shows the influence of orifice diameter and location on combustion oscillations in a 40-mm duct with an upstream length of 22 diameters. A significant reduction in sound intensity is evident where the orifice is located in the half of the upstream duct nearer the flameholder, and the reduction improves as the orifice is moved downstream; the smaller orifices are more effective than larger ones.

Figure 4b shows the influence of orifice location and diameter in a duct with an upstream length of 30 diameters. Combustion instability for this duct length is associated with a three-quarter-wave frequency in contrast with a quarter-wave frequency for upstream lengths less than 25 diameters. Reduction in sound intensity is observed at all orifice locations except near a pressure antinode of the three-quarter-wave frequency, where rough combustion associated with the three-quarter-wave frequency is observed. The reduced sound intensity at orifice locations between 6 and 13 diameters from the

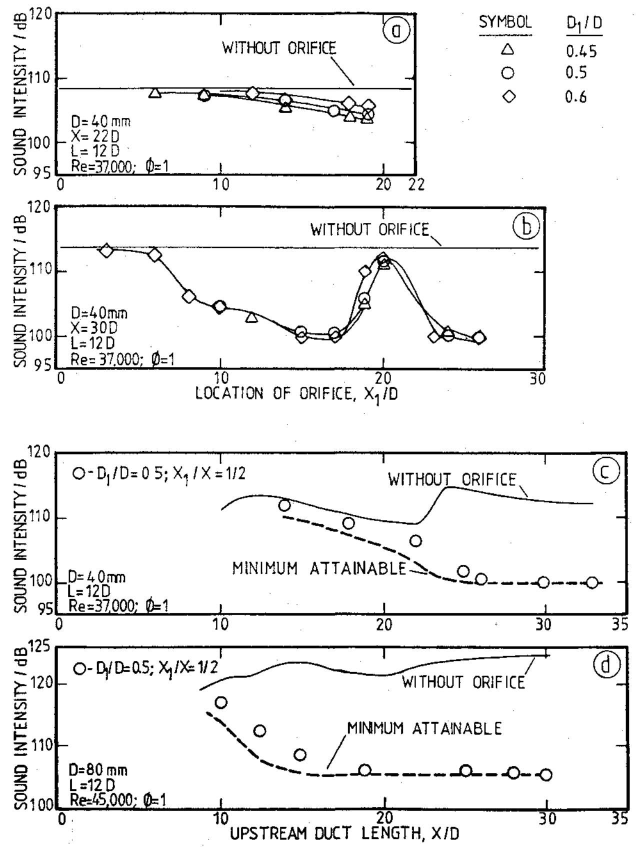

Fig. 4 Suppression of oscillations in duct with acoustically closed end.

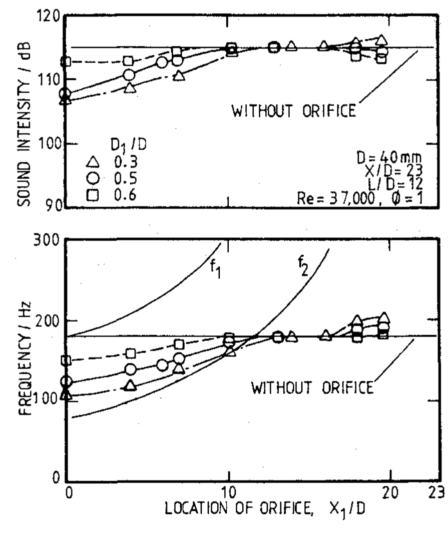

Fig. 5 Influence of single orifice on oscillations in duct with open upstream end.

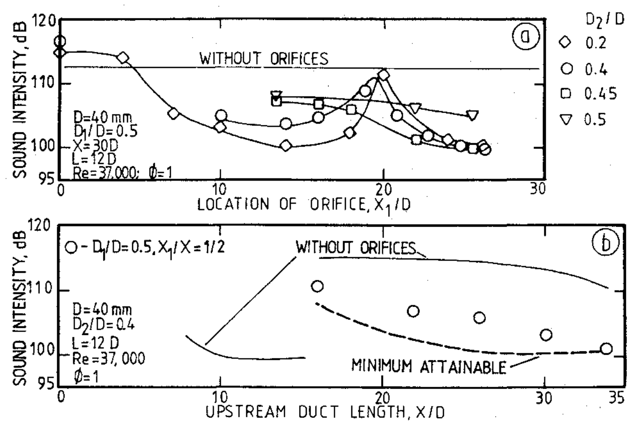

Fig. 6 Suppression of oscillations in duct with open end using pair of orifices.

upstream end is mainly due to the fact that the location of the orifice close to the node of the three-quarter-wave frequency results in oscillations associated with a quarter-wave frequency with lower sound intensity than those associated with the higher harmonic. With the orifice moved further downstream, oscillations are suppressed more effectively.

Figures 4c and 4d, respectively, show the influence of upstream duct length on the suppression of oscillations in 40- and 80-mm ducts. In 40-mm ducts, the maximum possible reduction in sound intensity increases from 4 dB for an upstream length of 15 diameters to over 12 dB for lengths exceeding 25 diameters. In 80-mm ducts, the reduction in sound intensity increases from 4 dB at 10 diameters to around 20 dB at 15 diameters. The maximum reduction in sound intensity is achieved when the oscillations associated with the dominant frequency are fully suppressed and the sound intensity falls to the value observed in smooth combustion. The larger reduction in sound intensity in the 80-mm duct is due to the larger difference in sound intensity between smooth and rough combustion in the larger duct, and the relatively shorter length at which effective suppression is achieved is associated with the fact that the minimum duct length at which oscillations could be effectively suppressed is nearly a half-wavelength of the maximum value of the dominant frequency, and the maximum reduction in sound intensity was achieved with the orifice located halfway between the swirl register and the flameholder. A 100% increase in the diameter of the duct is accompanied by a mere 20% decrease in the maximum value of the dominant frequency, and the decrease in the maximum value of the frequency with diameter probably occurs because larger combustor duct diameters are less capable of sustaining higher-frequency oscillations. The location of a second orifice of diameter as large as 0.7 D about a third of the upstream duct length from the upstream end in long ducts prevented the onset of strong oscillations associated with the three-quarter-wave frequency and permitted the effective suppression of oscillations at all orifice locations in the half of the upstream duct nearer the flameholder.

The use of sharp-edged orifices for suppressing oscillations entails pressure losses, and their replacement by smooth convergent-divergent nozzles would reduce them. The required range of nozzle diameters, however, was on average 15% smaller than the orifices, and the difference relates to the vena-contracta effect in the orifices. The pressure loss in an orifice of diameter 0.5 D is estimated at 9.0 $U_0^2/2$ compared with 3.1 $U_0^2/2$ for a nozzle of equal effectiveness, and that in an orifice of diameter 0.6 D is 4.1 $U_0^2/2$ compared with 1.3 $U_0^2/2$ for an equivalent nozzle.

Open-Ended Duct with Single Orifice

The influence of orifice diameter and location on combustion oscillations in an open-ended duct with a single orifice located upstream of the flameholder was examined for upstream duct lengths between 10 and 40 diameters, using orifices of diameter between 0.15 and 0.8 D. Orifices smaller than 0.25 D acted like acoustically closed ends, and those larger than 0.75 D had no significant effect on the oscillations.

Figure 5 shows the variation of sound intensity and the dominant frequency for an upstream length of 23 diameters at a Reynolds number of 37,000. The frequency assumes values between the half-wave frequency for the entire upstream length and the quarter-wave frequency based on the length between the orifice and the flameholder, with the pressure antinode located between the center of the upstream duct length and the position of the orifice. A decrease in orifice diameter increased the acoustic impedance and moved the antinode closer to the orifice and the frequency closer to the quarter-wave frequency. Results for upstream lengths between 16 and 35 diameters were similar, with the rough combustion at all orifice locations with the quarter-wave frequency upstream of the orifice having no influence on the oscillations. The use of an orifice in ducts with upstream lengths less than 16 diameters gave rise to rough combustion, in contrast to ducts of similar length without an orifice. The likelihood of combustion instability increased with a decrease in orifice diameter.

With upstream lengths exceeding 35 diameters, oscillations are associated with a full wave. With an orifice located at the center of the upstream duct 40 diameters in length, oscillations were associated with a half-wave frequency instead of the full-wave frequency and, with the orifice a quarter of the duct length from the upstream end of the flameholder, the oscillations remained in the full-wave frequency. The quarter-wave frequency upstream of the orifice did not have any influence on the oscillations.

Suppression of Oscillations in Open-Ended Ducts

The suppression of oscillations in ducts with an acoustically closed end using a single orifice implies a similar possibility in open-ended ducts, this time using a pair of orifices with one located at the upstream end and the other some distance upstream of the flameholder. The influence of orifice diameters and the location of the orifice immediately upstream of the flameholder was examined in a 40-mm duct with upstream lengths between 16 and 36 diameters. Since upstream lengths less than 16 diameters did not give rise to rough combustion, the suppression of oscillations with orifices was not examined in detail for these lengths.

Figure 6a shows the variation of the sound intensity with the location of an orifice of diameter $D_1 = 0.5\ D$ for different diameters D_2 of the orifice at the upstream end in a duct of upstream length 30 diameters at a Reynolds number of 37,000. The results for D_2 less than 0.4 D are in qualitative agreement with those in Fig. 4b for a duct with a closed upstream end. With an upstream orifice of diameter 0.45 D, effective suppression occurs only with the other orifice located close to the flameholder. With the diameter of the orifice at the upstream end increased to 0.5 D, the reduction in sound intensity is poor. The suppression of oscillations is possible with a pair of orifices but not with a single orifice, because the mechanism of suppression involves the interaction between a quarter-wave in the duct section immediately upstream of the flameholder and a half-wave in the section between the two orifices. Interaction between the two frequencies weakens with a decrease in the impedance of the orifice at the upstream end, and with the larger orifices, longer upstream lengths are necessary to set up half-wave frequencies that can effectively interact with the quarter-wave frequency in the section close to the flameholder.

Figure 6b shows the influence of upstream duct length with an orifice of diameter 0.4 D at the upstream end and an orifice of diameter 0.5 D immediately upstream of the flameholder. It appears that the suppression of oscillations in open-ended ducts is possible with upstream lengths comparable with those for ducts with acoustically closed ends. With larger orifices at the upstream end, however, longer upstream duct lengths may be necessary to be equally effective. The use of convergent-divergent nozzles in place of orifices was examined, and equivalent nozzle diameters were 15% less than orifice diameters.

Conclusions

The following five points summarize the main findings of the article.

1) Flammability and stability limits in ducts with acoustically closed and open ends have been measured and the effect of duct diameter established. In ducts with an acoustically closed end, rough combustion was observed at all upstream lengths for which combustion could be achieved at equivalence ratios up to stoichiometry. The use of short upstream lengths in open-ended ducts such that the half-wave frequency is significantly larger than the maximum frequency value associated with rough combustion enables smooth combustion across flammability limits.

2) Sharp bends have a high acoustic impedance which is not, however, strong enough to influence combustion oscillations, except for a narrow range of upstream lengths and to a small extent.

3) The suppression of oscillations in ducts with an acoustically closed end by proper location of an orifice is possible for upstream lengths exceeding 15 diameters in 40-mm ducts, and appears to be achieved by the interaction between a quarter-wave frequency in the duct section between the orifice and the flameholder and a half-wave in the duct section upstream of the orifice. The reduction in sound intensity increases to 12 dB for upstream lengths exceeding 25 diameters. In 80-mm ducts, the suppression of oscillations can be achieved in the same way with a reduction of 4 dB for an upstream length of 10 diameters and around 20 dB with lengths exceeding 15 diameters.

4) Oscillations could be suppressed in open-ended ducts using a pair of orifices, but not using a single orifice, for upstream lengths comparable with those for orifices with a closed end.

5) Smooth convergent-divergent nozzles could be used in place of orifices for the purpose of suppressing oscillations.

Acknowledgment

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