# ACOUSTIC CONTROL OF THE MIXING PROCESSES IN A GAS TURBINE COMBUSTOR

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## ABSTRACT

The air mixing processes in a gas turbine combustor control the lifetime of the turbine via the combustor exit plane temperature distribution, as well as the efficient burning of the fuel. Consequently an original technique has been developed to acoustically control the dilution-air jet mixing processes which govern the exit plane temperature distribution. This has resulted in a small combustor of normal design, employing the technique, being successfully tested up to the "half-load" condition. The ability to selectively and progressively control the temperature pattern was convincingly demonstrated. Acoustic driver power requirements were minimal. The pulsed dilution-jet flows develop toroidal vortices and improved mixing is indicated. The pressure loss, the overall combustion efficiency and other combustor performance factors were insignificantly affected by the acoustic drive. The study contributes to the design of combustors such that control may be exercised over the air jet mixing processes.

## RÉSUMÉ

Le processus de mélange d'air et de combustible dans la chambre de combustion d'une turbine à gaz contrôle la durée de vie de la turbine par la distribution uniforme de la température à la sortie de la chambre de combustion, de même que l'utilisation efficace du combustible. Par conséquent, on a mis au point une nouvelle technique visant à contrôler acoustiquement le processus de mélange par jets d'air qui règle la répartition de température à la sortie. Cette technique a conduit à l'élaboration d'une petite chambre de combustion de modèle courant qui a été soumise avec succès à des essais dans des conditions de charge atteignant la moitié de sa capacité. Il a été démontré de façon convaincante que l'on peut régler les variations de température de manière sélective et progressive. Les exigences en puissance acoustique se sont avérées minimes. Les jets d'air de dilution créent des tourbillons toroïdaux et il en résulte un meilleur mélange. Les effets de la commande acoustique sur la perte de pression, l'efficacité globale de la combustion ainsi que d'autres facteurs reliés à la performance de la chambre de combustion ont été de peu d'importance. Cette étude contribue à la conception de chambres de combustion à l'intérieur desquelles il est possible de régler le processus de mélange par jets d'air.

## NOMENCLATURE

| | |
|---|---|
| A/F | Air/fuel ratio (by mass flow rate) |
| f | Frequency |
| $\dot{m}_a$ | Air mass flow rate |
| $\dot{m}_f$ | Fuel mass flow rate |
| $M_{ref}$ | Reference Mach Number based on maximum I. DIA. of casing |
| $P_2$ | Inlet static pressure |
| r | Radial position |
| $S_t$ | Strouhal Number |
| $T$[1] | Temperature |
| $T_2$ | Inlet temperature |
| $T_3$ | Exit plane temperature |
| $T_{3m}$ | Exit plane mean temperature |
| $T_{31} \ldots T_{36}$ | Traversing thermocouples |
| $T_{3r}$ | Exit plane mean 'radial' temperature |
| $\bar{T}$ | Exit plane dimensionless temperature |
| $\bar{T}_r$ | Exit plane dimensionless 'radial' temperature |
| w | Thermocouple displacement from inside wall of combustor exit duct |
| $\phi$ | Equivalence ratio $\left(\frac{\text{Stoic A/F}}{\text{Actual A/F}}\right)$ |

## INTRODUCTION

A previous study on "The Acoustically Excited Flame" (1)[2] showed that toroidal or ring vortices were shed from a burner nozzle, Fig. 1(a), when the air-fuel mixture flow was modulated with sufficient amplitude by an upstream loudspeaker driver. The vortices strongly disturbed the flame burning at the orifice, Figs. 1(b) and 1(c), and it was apparent that extra air was entrained from the surroundings. It was also indicated that the vortex strength, and induced mixing effects, might be dependent upon the strength of the acoustic pulsations promoting the vortices. An investigation, via high speed schlieren pictures, of the phenomena, Fig. 2, confirmed its physical nature.

An extensive literature on vortex phenomena exists, and the evolution of toroidal vortices in orifice/nozzle jet flows is well known (2), (3), (4). Velocity distributions in vortex rings were studied by Sullivan, et al., (5); they controlled the strength and vortex core size by the duration and amplitude of the flow pulse generated by a loudspeaker driver. Bryer (6) used rotating flat delta plates to produce vortices in air or water vessels thereby improving the mixing efficiency above that of conventional stirrers. Vortex rings agitating atmospheric inversion layers was proposed by Mattingly (7) who also showed, using a model wing to generate wing tip vortices that the

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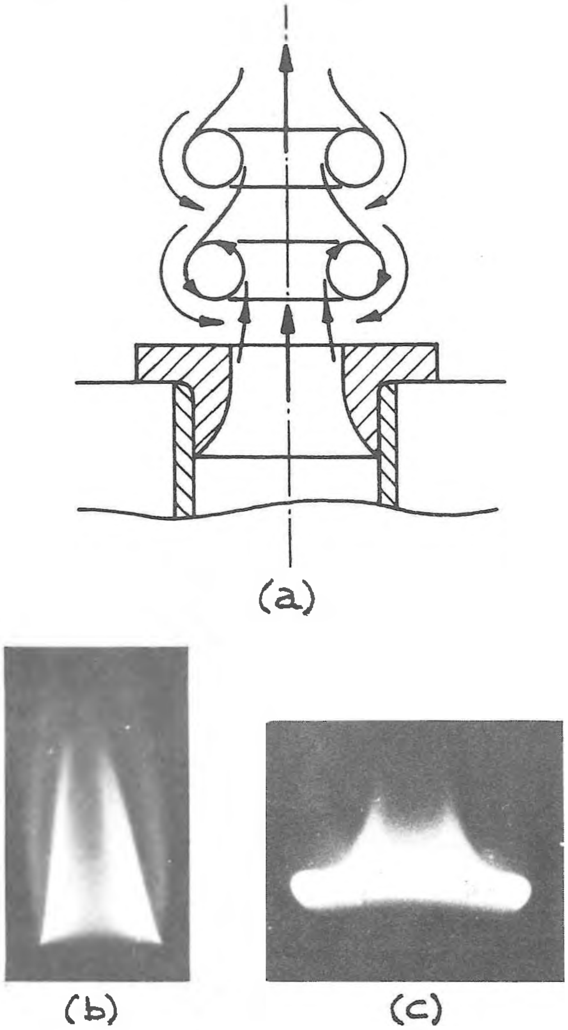
[1] This is strictly stagnation temperature, but because of low flow velocity stagnation temperature closely approximates static temperature and the distinction can be ignored.

[2] Designates a reference at the end of the paper.

vortices could be destroyed by an external vortex propagating through them. Baird, et al., (8) studied the pulsed generation of vortex rings as a design basis for mixing applications.



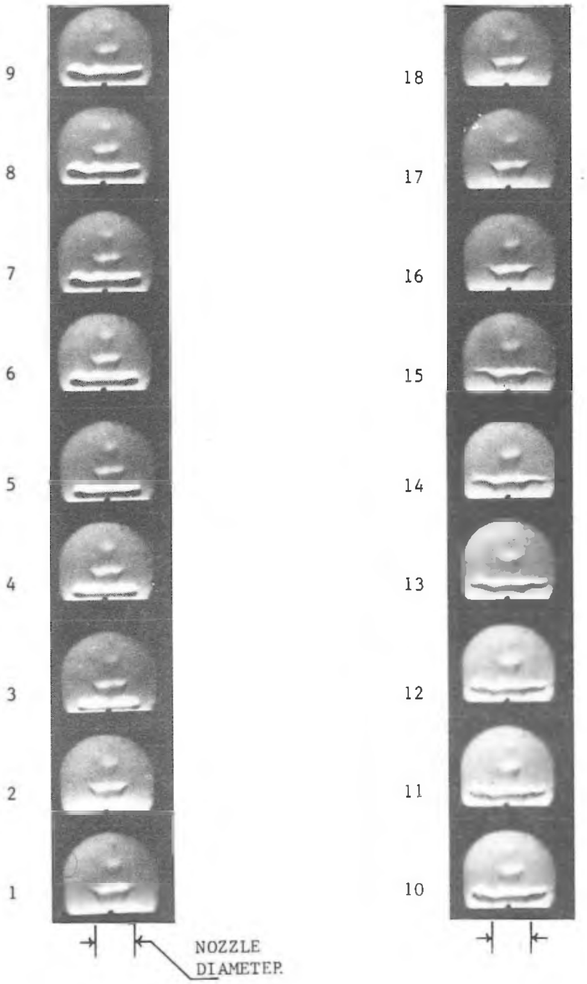


Fig. 1 Pulsating Flow from a Burner Nozzle.
(a) Interpretive Sketch of Flow
(b) Unexcited Flame, $\phi = 1.55$
(c) Excited Flame, f = 250 Hz, $\phi = 1.55$

Fig. 2 High Speed Schlieren Pictures of Pulsating Flame at Burner Nozzle of Fig. 1. f = 250 Hz, $\phi = 1.67$, framing rate 4016/s.

These considerations therefore suggested that it may be possible to acoustically control the jet mixing proceses in a gas turbine type combustor to give beneficial results. In particular the dilution jet flows of such a combustor, used to control the exit plane temperature distribution, might be made more effective by deliberately introducing toroidal vortices with the jet flows. Fig. 3, shows a cross section through the typical tubular combustor used in the latest experimental work, it indicates the air distribution in relation to the primary, secondary and dilution zones. At the entrance to the flame tube, air enters an annulus containing swirl vanes necessary to produce a recirculation zone about the axis, which stabilizes the burning fuel gas (natural gas) injected as shown. Air from the main annulus enters 10 pairs of nozzles in the flame tube wall, to produce jets which mix air with the recirculation zone, in order to bring the combustion to about 80% completion at the end of the primary zone. In the secondary zone 20 more nozzles create air jets to mix air with the combustion products from the primary zone and raise the combustion efficiency to about 100%. The gas temperature at the end of the secondary zone (≅ 1720 K) is too great for exit to the turbine, and must be cooled by mixing more cold air from the annulus by means of the six air jets from the nozzles in the dilution zone. The flame tube walls are kept cool by means of the annular air flows along the walls. There are therefore three zones where air jets carry out mixing in order to control events in the combustor. The dilution-air jets are technically the easiest to acoustically drive, and the mixing events only control the exit plane temperature magnitude and distribution since combustion is complete. A satisfactory temperature distribution is necessary to ensure that the turbine is not exposed to excessive temperatures otherwise its life would be short. Thus it was decided to establish the success of the concept by modulating the dilution-air jets only.

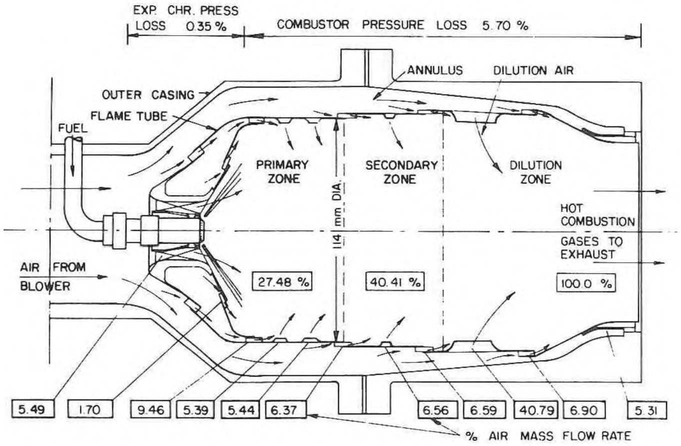


Fig. 3 Cross Section Through Typical Tubular Combustor Showing the Air Distribution.

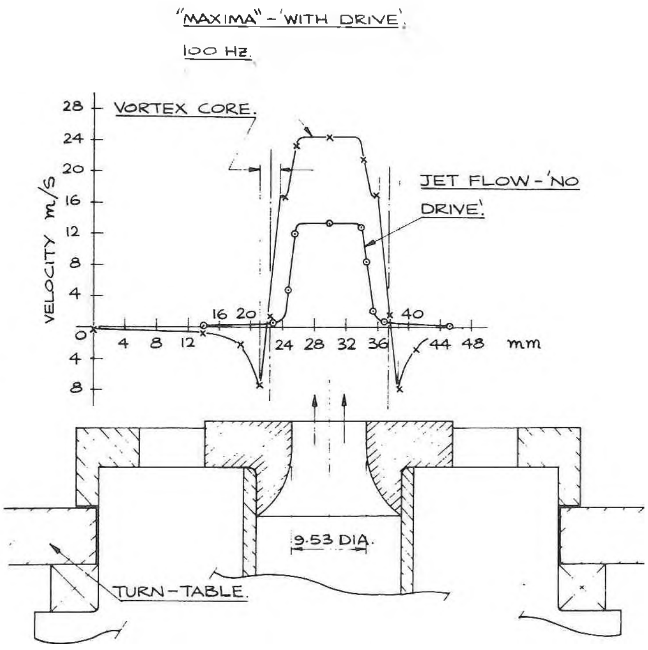


Fig. 4 Flow Velocity Profiles, With and Without Acoustic Drive, for Plane Through Nozzle Axis. Measurements 9.5 mm Above Nozzle Face. Power to Driver 4.8 W.

Two experimental approaches have now been examined (9), (10). The first involved a simple combustor to establish the concept at flow conditions that would be easy to manage. The second developed from the success of the initial concept experiments to utilise a tubular combustor of normal design, Fig. 3, operating at more representative flow conditions. This paper is essentially a review of this work, (9), (10), placed into better perspective by recent literature research.

The work of Anderson (2), (3), Becker and Massaro (4), Crow and Champagne (11) and Kibens (12), show that an acoustically excited jet exhibits two instability mechanisms. The first mechanism involves the thin laminar boundary layer which forms around the jet as it issues from the nozzle lip. The boundary layer is unstable and on excitation forms waves which then roll up into toroidal vortices on progression along the jet. The second mechanism concerns the instability of the jet-column, which on excitation develops wave motion growing into a train of toroidal vortices, which at optimum conditions are strong enough to disintegrate the jet column. Depending on the excitation strength the jet column response is strongest for a Strouhal number range $S_t$ from about 0.2 to 0.5. Optimum response occurs at $S_t \cong 0.3$. Coupling between the two modes can occur at a common frequency under favourable jet conditions. For a turbulent boundary layer it would appear that the jet-column mode is the only one possible.

Toroidal vortices have been harmonically produced on an air jet by Sarohia and Massier (13), and Heavens (14), at a 0.6 Mach number and Reynolds numbers in the $10^5 - 10^6$ range. Heavens (14) also excited the jet flow by means of an upstream spark generated pulse at 0.8 Mach number and a $2 \times 10^5$ Reynolds number. In comparison the combustor jet flows represent a more modest flow regime, in terms of excitation, since the maximum Mach and Reynolds numbers are about 0.23 and $10^5$ respectively. Excitation frequencies used by other workers have been up to 20 kHz (14). Crow and Champagne (11) showed for a low value of excitation that the entrained volume flow increased 32% over the unexcited case. Binder and Favre-Marinet (15) established that the entrainment rate increased by 90% over the unexcited case for much stronger excitation than (11). Sarohia and Massier (13) deduced from centre-line velocity measurements that toroidal vortices produced by acoustic excitation increased the jet entrainment over the unexcited case, and Bremhorst and Harch (16) made measurements for a fully pulsed subsonic air jet showing that the entrainment and entrainment rate were considerably higher than for a steady jet. Direct measurement of entrained mass flow rates for unsteady jets do not appear to have been carried out. It is clear from the literature therefore that unsteady jet flows and their associated phenomena have superior mixing properties over steady jets for flow conditions of technical interest, and therefore technical applications should be possible.

## INITIAL CONCEPT DEVELOPMENT FOR DILUTION-AIR JETS

### Pulsed Jet flow Velocity Field Profile

In order to establish some physical "feel" for the nature of a pulsating jet flow an air jet, flowing vertically into the atmosphere at room temperature, was created by a 9.53 mm dia bore nozzle. A loudspeaker driver excited the flow upstream of the nozzle sinusoidally at 100 Hz. Velocity profiles were measured using a DISA hot wire anemometer, for the unexcited flow and for an excitation power at the loudspeaker driver of 4.8 W. The anemometer output was recorded on magnetic tape then played back for oscillographic recording and analysis on a Honeywell 1508 Visicorder. Fig. 4 shows measured velocity profiles across a plane one nozzle diameter downstream of the nozzle exit plane and with the probe traversed normally to and through the nozzle centre line. The velocity profile with acoustic excitation shows "maximum" measured velocities, ie., the peak velocity recorded as the flow pulsation passes through the measurement plane. This profile is what would be expected from a jet flow with superimposed toroidal vortex (17). The measurements indicate that the field of influence of the jet is about quadrupled by the vortex superposition, there is considerable shearing action across the vortex core, and the maximum pulse velocity is about twice the steady jet velocity. The vortex is shown to have induced a downwards flow in the outer field and presumably entrainment from this region into the jet flow. The pulsed flow and vortices were plainly observable at over six nozzle diameters downstream, although turbulent breakdown was evident, hence it may be anticipated that the vortex mixing effects could also persist to this distance. The average velocity of the core flow was not significantly different from that of the unmodulated flow and hence the exit mass flow rate may be considered to be unaffected by the acoustic drive for this case.

## Primitive Combustor With Acoustic Control of the Dilution-Air Flows.

A simple combustor was constructed by mounting a flame tube in a small wind tunnel as shown in Fig. 5. For ease of manufacture a hemispherical "pepper pot" stabilised the primary zone where natural gas was burnt. Dilution-air was brought into the flame tube by seven radial stainless steel guide tubes feeding nozzles in the flame tube walls. The mouthpiece, at right angles to the guide tube, channels air to the flame tube whilst the cold end of the guide tube is connected via a drive tube to a loudspeaker driver. The drivers were modulated by means of a three channel amplifier in conjunction with a signal generator. Driver power was measured by means of A.C. voltmeters and ammeters, since the power factor had previously been shown to be close to unity. Temperature profiles at the combustor exit were measured using a shielded thermocouple, and instrumentation was provided to measure fuel and air mass flow rates. Such a combustor is not typical of modern combustors but is adequate as a slave for the dilution-flow modulation experiments.

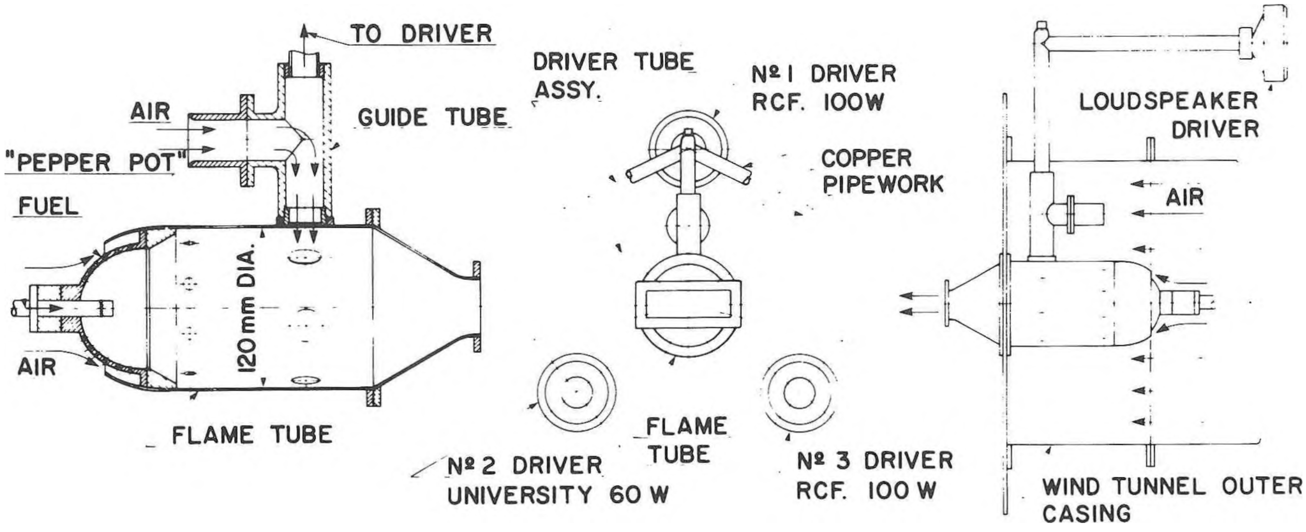
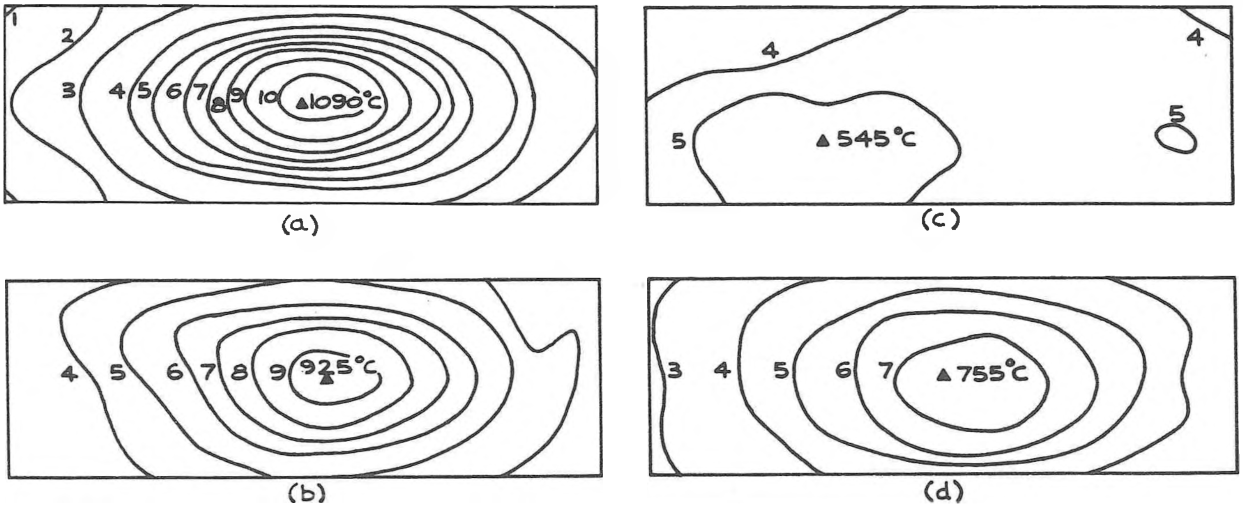


Fig. 5 Primitive Combustor:Flame Tube Assembly, Drive Tubes Arrangement, Flame Tube Mounted in the Wind Tunnel.

## The Temperature Profile Measurements.

Fig 6. shows exit plane temperature maps for no acoustic drive and with approximately uniform acoustic drive. The temperature contours were obtained by interpolation from rectangular cartesian measurements, hence experimental points are not shown. The "no-drive" profile shows the combustor to have a very 'peaky' temperature distribution, unacceptable for a gas turbine combustor, but ideal for demonstration of the acoustic control concept. Thus for the 'with-drive' condition it is readily seen from Fig. 6 that considerable "flattening" of the temperature distribution has been achieved, and appears to depend on frequency. At 104 Hz the acoustic drive has reduced the temperature peak by about 165°C, at 120.5 Hz a spectacular reduction of about 545°C was achieved, and at 135 Hz about 335°C reduction occurred. The enhanced effectiveness at 120.5 Hz is probably due to the fact that this was the "organ pipe" resonance frequency of the driver tube assemblies. The difference in effectiveness between the 104 Hz and 135 Hz tests may not be simply due to the frequency response of the loudspeaker-drive tube system but also may be due to the frequency response of the fluid processes. Increasing the driver power at 135 Hz progressively flattened the temperature distribution; the temperature profiles being shown in ref. (9). Overall it may be concluded that acoustic modulation of the dilution-air flows can progressively control the exit plane temperature distribution for the modest flow conditions tested.



(a) (c) (b) (d)

Fig. 6 Exit Plane Temperature Maps (100°C Contours), A/F = 81.
(a) No-Drive
(b) f = 104 Hz, Total Driver Power 73 W
(c) f = 120.5 Hz, Total Driver Power 70 W
(d) f = 135 Hz, Total Driver Power 76 W

## CONCEPT DEVELOPMENT FOR DILUTION-AIR JETS IN A PRACTICAL GAS TURBINE COMBUSTOR

The initial concept work was limited by the fact that the combustor was not typical of modern practice and the flow reference Mach number, $M_{ref}$ only corresponded to one tenth of "full-load" conditions. Thus a test rig was built to test a small typical tubular combustor, Fig. 3, up to "half-load" conditions, based on $M_{ref}$ (loading was limited by the air blower available). $M_{ref}$, as is usual, was calculated at the maximum inside diameter of the casing (142.9 mm dia.) for cold flow.

## The Combustor Test Rig and Acoustic Control Method.

Air for combustion was supplied by a small centrifugal blower to a venturimeter thence to the combustor. Natural gas, from high pressure bottles, was metered by a choked orifice before injection into the swirl stabilised primary zone. Full instrumentation was provided to assess the performance of the combustor, and in particular the exit plane temperature distribution was measured by six, shielded, radially traversed thermocouples circumferentially spaced at 30°. The temperature was measured at 11 points across each of the six diameters so defined, giving a total of 66 measurement positions. This number and the radial position specified for each measurement ensured that an accurate analysis of the combustor performance could be made.

The combustor geometry presented difficulties to devising a method for acoustically controlling the dilution-air flows. However, after some experimentation success was finally achieved by rerouting the dilution-air such that it was tapped-off upstream of the combustor inlet, run through 6 tubes parallel to the combustor axis outside of the casing, then each tube turned inwards to pass normally to the axis, through the casing, and connect with a dilution hole in the flame tube. Thus air from the annulus no longer

TABLE NUMBER I
RELAVANT TEST CONDITIONS

| Test | $\dot{m}_a$ kg/s | [3] A/F | φ Overall | $T_2$ K | $p_2$ kP$_a$ | $M_{ref}$ | Driver No. and "Max" Power W @ 220 Hz | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1 | 2 | 3 |
| 9 | 0.0984 | 62.9 | 0.272 | 308 | 90.28 | 0.0172 | 57.4 | 54.2 | 57.4 |
| 10 | 0.1344 | 67.3 | 0.255 | 307 | 90.15 | 0.0239 | 59.0 | 59.1 | 59.0 |
| 11 | 0.0981 | 62.5 | 0.275 | 309 | 89.76 | 0.0174 | 18.1 | 19.3 | 18.1 |
| 13 | 0.0978 | 62.7 | 0.274 | 309 | 89.57 | 0.0174 | - | - | 71.7 |
| 14 | 0.0974 | 63.7 | 0.269 | 310 | 89.09 | 0.0174 | - | - | 12.4 |
| 15 | 0.1693 | 90.5 | 0.190 | 307 | 90.42 | 0.0302 | - | - | 73.5 |
| 22 | 0.0983 | 55.7 | 0.308 | 307 | 90.30 | 0.0170 | - | - | 12.6 |
| 23 | 0.0984 | 90.3 | 0.190 | 306 | 90.25 | 0.0170 | - | - | 12.5 |
| Theoretical Full Load Nominal | 1.1657 | 60.4 | 0.286 | 476 | 395.4 | 0.057 | STANDARD COMBUSTOR | | |

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[3] Stoichiometric A/F = 17.16

entered the dilution holes. Air by-pass tube pairs were connected by 'T' junctions to a driver tube and loudspeaker, which allowed for easy variation of frequency and power for modulating the flow. Fig. 7 shows details of the arrangement. To prevent acoustic energy passing upstream via the by-pass tubes Helmholtz resonators were attached as shown in Fig. 7. Unfortunately, despite bench testing of a driver tube by-pass tubes system, the Helmholtz resonators proved to be ineffective. However, the system was still capable of modulating the dilution-air flows, and the strongest resonance mode of the full assembly was found to be at 220 Hz by progressively changing the drive frequency (keeping power constant) and observing the effect on the exit plane temperature distribution. Table I presents the range of test conditions used and clearly shows that "half-load" conditions, based on $M_{ref}$, were not exceeded. Also the table shows that the combustor was tested over approximately its full range of air:fuel ratios (A/F).

The exit plane chromel-alumel thermocouples could be positioned to within ± 0.3% of the exit diameter (85.39 mm) and they measured temperature to within ±1½% over the experimental range. The air and fuel mass flow rates were accurate to ± 1½% and ± 3% respectively.

The same signal generator supplied a sinusoidal voltage to the loudspeaker amplifiers, and input power to a loudspeaker was measured by an A.C. voltmeter and ammeter; the "maximum" power was then computed from the product of current and voltage.

## Test Results - Temperature Patterns.

The objectives of the temperature profile measurements were to

(a) establish that the temperature pattern was satisfactory and typical without acoustic drive,

(b) establish that the temperature pattern remained approximately constant with reasonable changes of running condition, and

(c) establish the magnitude of changes in the temperature distribution caused by the acoustic drive.

For ease of comparison the temperature maps are presented in terms of the dimensionless local temperature defined by

$$\bar{T}\% = \frac{T_3 - T_{3m}}{T_{3m} - T_2} \times 100$$

Also the six readings at one radial position were averaged, non-dimensionalised in terms of

$$\bar{\bar{T}}_r = \frac{T_{3r} - T_{3m}}{T_{3m} - T_2}$$

and plotted against radial position to give dimensionless 'radial' temperature profiles. These indicate approximately the radial temperature profiles in the annular channel upstream of the nozzle guide vanes and eventually 'seen' by the turbine blades.

Figs. 8 to 10 show sample 'no-drive' exit plane dimensionless temperature maps, and their similarity is readily seen as was the case for the other tests. Fig. 11 typifies the 'no-drive' 'radial' temperature profiles, good similarity between tests having been obtained. Repeatability between tests of similar $\dot{m}_a$ and A/F was satisfactory, and the results show a temperature pattern that is acceptable and typical for this type of combustor without acoustic drive.

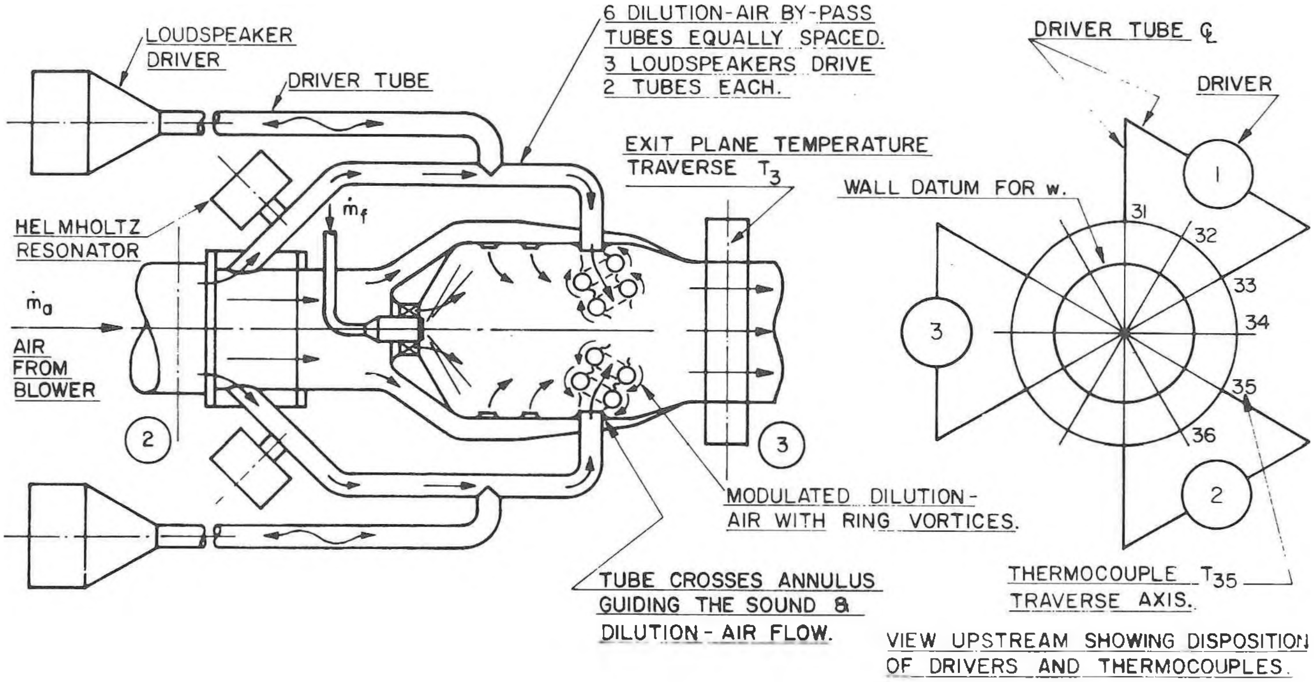

Fig. 7 Schema of Final Apparatus for Acoustic Control of Dilution Mixing Processes.

Typical dimensionless temperature distribution data for the 'with-drive' condition at 220 Hz is also shown in Figs. 8 to 11. Two driver patterns were explored as well as several driver powers, Table I. Little more than a cursory glance at the data is necessary to realise that acoustic modulation has been successful in changing the exit plane temperature pattern (also confirmed by the data not shown). This has been accomplished for an acceptable temperature pattern in contrast to that of the primitive combustor for the initial concept tests. There was no significant change in the exit plane mean temperature $T_{3m}$, as would be expected for mixing process effects only. Fig. 8, for uniform driving, shows an evening out of the temperature distribution, but the hot spot remains (at the 3 o'clock position looking upstream), although reduced in size. By only driving No. 3 loudspeaker at the 9 o'clock position it was found that this temperature peak could be trimmed, although more driver power was required for the higher mass flow rate, Figs. 9 and 10. The trimming of the temperature peak together with the increase in temperature of the region closest to the driven ports (at 9 o'clock) suggests that the modulated dilution-air jets have greater penetration properties. Test 13, at low air mass flow rate, confirmed this by a strong reduction in the hot spot temperature and a strong increase near the wall at the 9 o'clock position. The data also showed that the effectiveness of the modulation increased with increase in driver power.

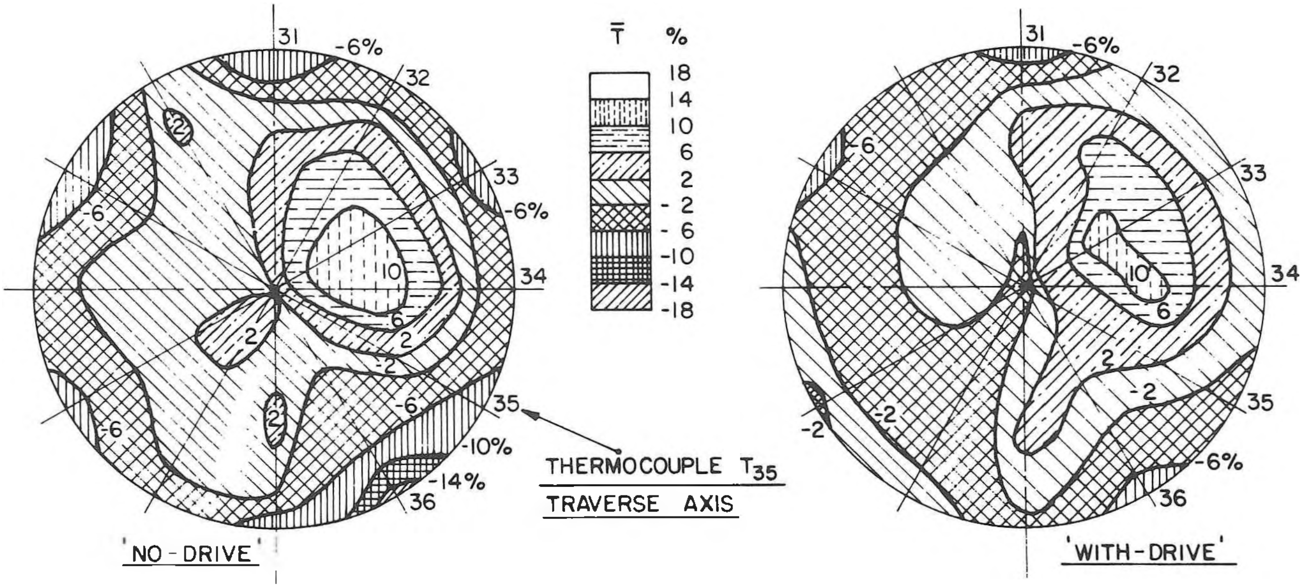

Fig. 8 Exit Plane Dimensionless Temperature Maps. Test Number 10. Views Looking Upstream. See Table Number I for Test Conditions.

The sensor of a hot film anemometer (Thermal Systems Inc.) was inserted radially through one of the by-pass tubes to a point inside the flame tube about one diameter downstream of the dilution-air port. Because of destruction of the sensor, measurements could only be made in cold air flows, but showed that over the test air mass flow rate range the modulated dilution-air jet flow pulsated with toroidal vortices superimposed on the flow. Figs. 9 and 10 show an evening out of the temperature pattern in the L.H. half sector suggesting better mixing effectiveness. The velocity profiles of Fig. 6 suggest that the effective mixing diameter of the dilution jet is about doubled by the toroidal vortex, thereby affecting a sector from about the 7 o'clock to 11 o'clock positions (for two ports). This coincides with the zone of improved mixing shown by Figs. 9 and 10 and is therefore probably due to vortex action.

Clearly from the evidence presented significant changes in the exit plane temperature distribution of a 'good' combustor are possible by acoustic control of the dilution mixing processes. Also the driver power required for significant effects is negligible when compared with the energy conversion rate of the combustor of 50 to 100 kW over the test range. Other combustor

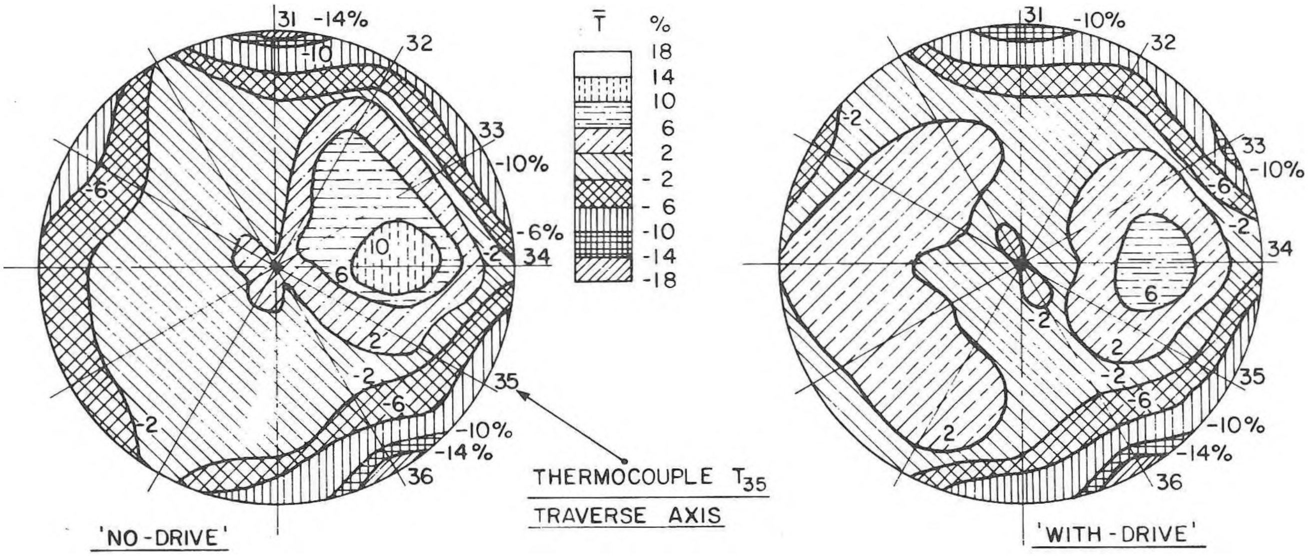

Fig. 9 Exit Plane Dimensionless Temperature Maps. Test Number 23. Views Looking Upstream.

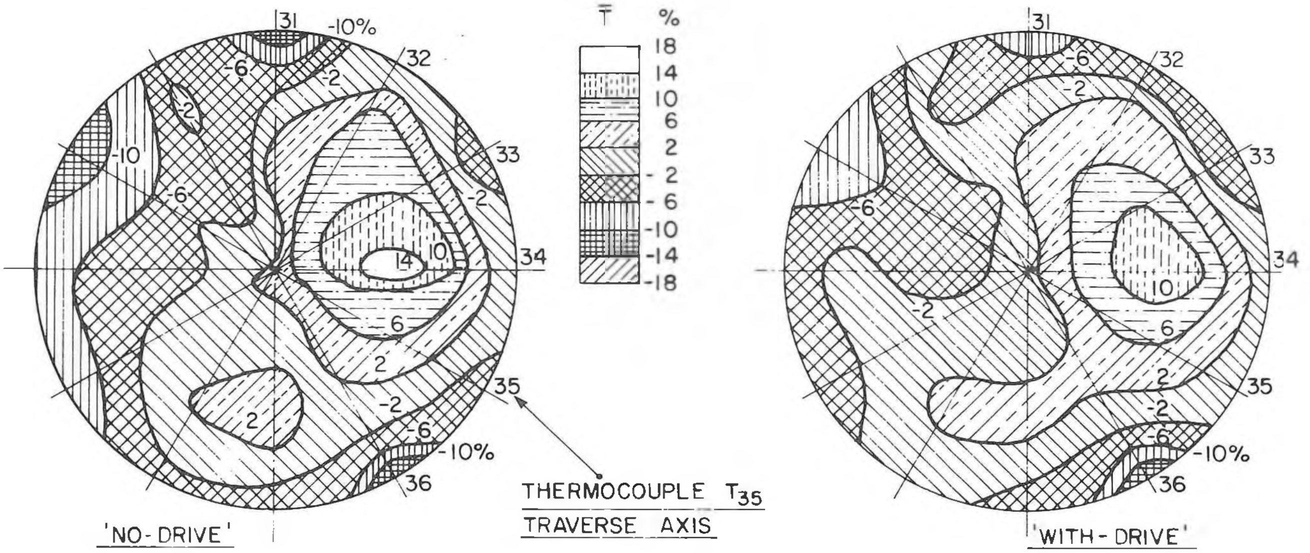

Fig. 10 Exit Plane Dimensionless Temperature Maps. Test Number 15. Views Looking Upstream.

performance parameters, such as pressure loss and overall combustion efficiency, were not significantly affected by the acoustic drive and in general no detrimental effects were observed.

## Strouhal Number Range of The Tests and Future Work.

Care was taken to drive the system close to its resonant mode (as for the primitive combustor) thus trying to make the most effective use of the power to the drivers. However, recent literature research has shown that operation at a Strouhal number from 0.2 to 0.5 is likely to produce the best response from the dilution-air jets. In comparison for these tests, at low $\dot{m}_a$ $S_t = 0.2$, whilst at high $\dot{m}_a$ ('half-load') $S_t = 0.1$. Thus at 'half-load' the Strouhal number match was poor and at 'low load' it was barely adequate, suggesting that more effective driving might take place at frequencies higher than 220 Hz provided that the driver system could be tuned to have a compatible resonance mode. In contrast for the primitive combustor $S_t$ ranged from 0.4 to 0.55, with $S_t = 0.5$ at resonance; a somewhat better match borne out by the observed temperature changes. Future experiments will be planned to better match the system resonance to the optimum Strouhal number.

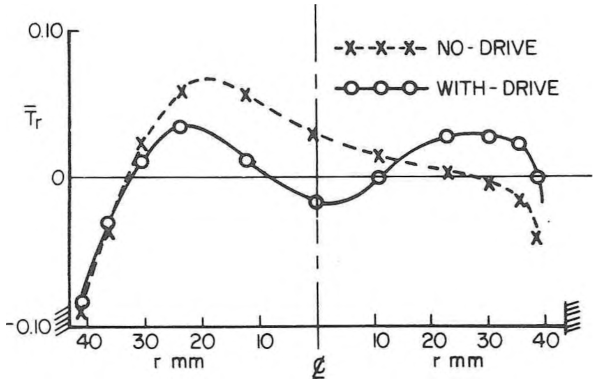

Fig. 11 Exit Plane Dimensionless 'Radial' Temperature Profiles. Test Number 23.

Development of the technique, for the dilution zone, up to 'full-load' operation has now taken place and a publication is forthcoming (18). Acoustic control of the primary zone mixing processes is perhaps of greater practical interest since improved combustion efficiency of this zone may result. Work to this end is now at an advanced stage. The current acoustic modulation system is clearly not very practical because of complexity and short running life. Research has therefore been initiated to produce a simpler and more reliable system, one that is entirely fluidic in nature for instance. Promising development to this end is taking place and a solution appears possible.

## CONCLUSIONS

A technique has been developed to acoustically control the mixing processes of the dilution-air jets of a small combustor of normal design. The nature of the acoustically modulated jet flows up to 'half-load' conditions has been established as that of a pulsating jet flow with superimposed toroidal vortices. The technique can be used to selectively and progressiv· control the exit plane temperature distribution. In particular, for an already good temperature pattern, it is possible to trim the temperature profile. The changes in temperature pattern caused by the acoustic drive indicate that the modulated jets have greater penetration properties and that improved mixing may be due to vortex action. Successful flow modulation was achieved by minimal power requirements for the loudspeaker drivers. Other combustor performance parameters, such as pressure loss and overall combustion efficiency, were not significantly affected by the acoustic drive and in general no detrimental effects were observed. The study contributes to the design of combustors such that control may be exercised over the air jet mixing processes.

## ACKNOWLEDGEMENT

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