EXPLOSIONS IN GAS TURBINE ENCLOSURES

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The current basis of safety in the event of a gas leak in a gas turbine acoustic enclosure is dilution ventilation. Additional research work has been undertaken to provide a sounder basis for assessing effective dilution ventilation. As part of this work an experimental study has been undertaken on the overpressures generated by small partial fills of the enclosure with a flammable congested gas cloud. This paper presents the results of this study.

INTRODUCTION

The gas supply to gas turbines is operated at high pressures and the possibility of a leak and explosion within the turbine acoustic enclosure has to be considered. The preferred basis of safety in the event of a gas leak is dilution ventilation. At present the recommended criterion for dilution ventilation design is that the 50% LEL enclosed iso-surface volume of leaked gas under alarm conditions should occupy no more than 0.1% of the enclosure volume. Earlier work[1,2] indicated that this criterion is both conservative and attainable. A further programme of work has since been undertaken to provide a sounder basis for the criterion and to provide data for the validation of computational fluid dynamic (CFD) modelling of gas leaks within acoustic enclosures.

One of the aims of the experimental part of the programme was to provide further data on the overpressures generated from gas clouds partially filling a small part of the enclosure, less than about 1%, including the effects of congestion within the cloud. Cubbage and Marshall[3] have investigated the pressures generated in combustion chambers by the ignition of pockets of gas/air mixture. In this study the gas pockets ranged in size from about 1% to 20% of the test chamber volume, but the gas mixture was uncongested and the size of the chamber, at $0.136\ m^3$, was very small. Studies have also been carried out on a much larger scale with congested clouds, though with partial fills well above the size of interest applicable to turbine acoustic enclosures. An example of such a study is the work reported by Chamberlain and Rowson[4] in a confined rig of about $8.5\ m^3$ internal volume. The partial fills used ranged from about 10% to 63%.

This paper presents the results of the ignition tests carried out to fulfil the above aim. The results may also be relevant to other applications where ventilation is used to restrict cloud size, or where strength is limited, eg weaker gas fired equipment at start up.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

THE ENCLOSURES

Two sizes of steel enclosure were used for the tests, constructed by bolting together 2.5 m cubic modules. The larger one, used for the quiescent and steady state tests, had internal dimensions of 2.5 m by 2.5 m by 14.9 m long, giving an internal volume of 93.1 m^3. The smaller one, which was just used for the quiescent tests, had internal dimensions of 2.5 m by 2.5 m by 2.35 m long, giving an internal volume of 14.7 m^3. To provide shielding of the air inlets from the wind, to reduce the effect of wind on the ventilation flow through the enclosure, and also to provide easier access into the enclosure, an additional module was positioned against the air inlet end of the enclosures. A schematic of the experimental arrangement for the 93.1 m^3 enclosure is given in Figure 1.

THE VENTILATION SYSTEM

The larger enclosure was ventilated using a variable speed centrifugal fan, mounted at one end of the enclosure, to draw air through the enclosure (see Figure 1).

The configuration used for the air outlets consisted of 16 square holes evenly distributed over the cross-section of the enclosure. This arrangement gave a nominal total open area for the outlets equal to 10% of the enclosure cross-sectional area (i.e. the area normal to the flow direction). To ensure as uniform flow as possible through the enclosure, a different configuration was used for the air inlets. This consisted of an array of 324 evenly distributed 50 mm diameter holes cut in the end of the enclosure. The nominal open area of the air inlets was 10% of the enclosure cross-sectional area.

CONGESTED GAS VOLUME

Congestion within the gas cloud was generated using obstacle configurations made from arrays of metal or plastic pipes. The aim was not to try and reproduce the exact geometry of the congestion around a gas turbine, but to produce levels of congestion that were representative of typical installations. For comparison purposes tests were also undertaken with no arrays, ie a gas cloud with no congestion.

Two pipe configurations, Arrangements A and B, were used in the tests. Arrangement A, giving the highest level of congestion, had a spacing of three pipe diameters between pipes, with adjacent rows orientated at right angles and the pipes staggered between every other row. Arrangement B had the same orientation of pipes, but with a spacing of five diameters between pipes. The pipe diameters used (12.5 mm, 25 mm or 50 mm) depended on the gas cloud size, so that irrespective of the cloud size the number of pipes within the cloud was the same. This resulted in Arrangement A having 16 pipes (four rows with four pipes per row) and Arrangement B having nine pipes (three rows with three pipes per row). The blockage ratio per row of pipes is approximately 0.22 for Arrangement A and 0.16 for Arrangement B.

The pipes were mounted in an obstacle cage (see Figure 2), fabricated from 25 mm angle iron. One side of the cage was closed with a metal plate, to simulate the body of the

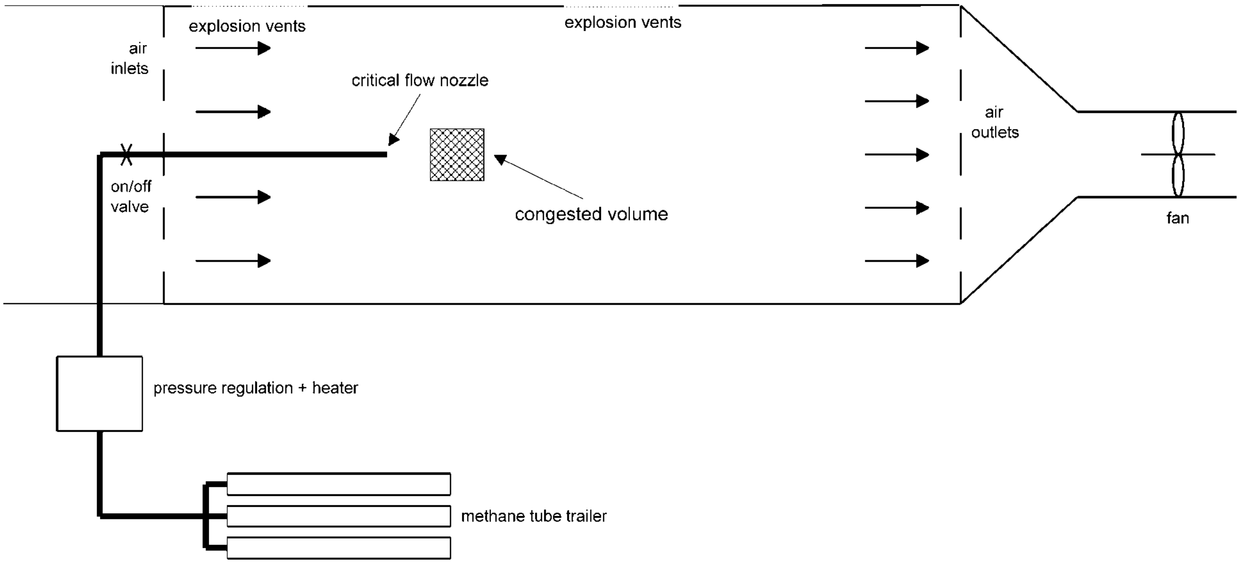

Figure 1. Schematic drawing of the experimental arrangement for the 93.1 m^3 enclosure (not to scale)

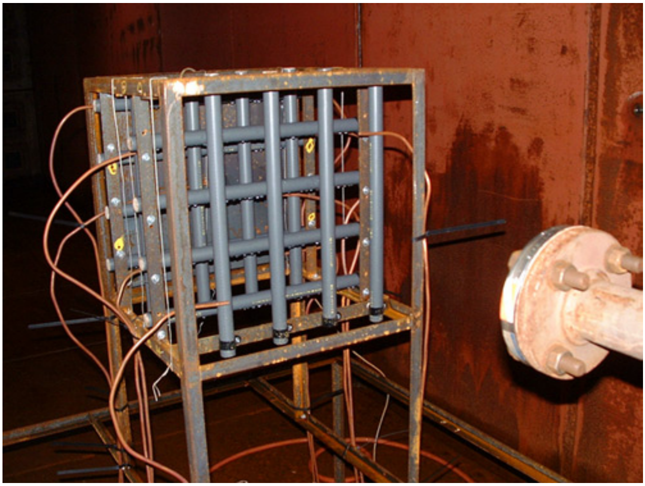

Figure 2. Obstacle cage with pipe array Arrangement A

gas turbine. A gas inlet and outlet and a mounting for a pressure transducer were incorporated in this plate. The congested volumes used were nominally 0.1%, 0.5% and 1% of the total enclosure volume.

THE GAS SUPPLY SYSTEM

For the quiescent tests the cage volume was purged with a pre-mixed stoichiometric methane/air mixture (9.5 $\pm$ 0.2% v/v methane). The air for the mixture was supplied from a small oil-less compressor and the methane from a cylinder (99.5% purity).

For the steady-state tests a stainless steel cylindrical throat type critical flow venturi nozzle, conforming to BS EN ISO 9300: 1995[5], was used as the leak source. The critical flow nozzle was bolted onto a 50 mm nominal bore pipe that extended into the enclosure, so that the nozzle outlet was located 5.2 m downstream of the air inlets of the 93.1 m^3 enclosure. The outlet of the nozzle was orientated so the gas would discharge along the centre line of the enclosure (see Figure 1). To allow continuous monitoring of the gas pressure and temperature on the upstream side of the critical flow nozzle, required to calculate the methane leak rate, a pressure transducer (Keller PA-21SR, 0–100 bar gauge) and a thermocouple (Type T, stainless steel sheathed) were mounted in the 50 mm diameter pipe.

The methane gas (99.5% purity) for the steady-state tests was supplied from a bank of manifolded cylinder pallets (16 pallets of 16 cylinders in each pallet), via a combined pressure regulation and heater unit. This unit consisted of a high capacity adjustable pressure regulator, electrically heated water bath, emergency shutdown valve and a high-level vent stack. Gas supply pressures upstream of the critical flow nozzle were set using the adjustable pressure regulator (0 to 40 bar). To prevent freezing up of the pressure regulator it was necessary to use the water bath to heat the gas entering the regulator. A pneumatically operated ball valve, located at the gas inlet end of the 50 mm diameter pipe (see Figure 1), was used to remotely start and stop the flow of methane into the enclosure.

THE IGNITION SOURCE

For the quiescent tests an electric match head (Vulcan Fuses supplied by Nobel Explosives) was used as the ignition source. These match heads contain a very small amount of pyrotechnic composition, which is ignited with an electric current. It is the resulting burning particles of composition that ignite the gas mixture. No information is available on the energy released by the match head, but it is estimated it is no more than tens of millijoules. The match head was located in the centre of the metal plate sealing one side of the obstacle cage, to simulate ignition at the gas turbine.

The electric match heads proved to be an unreliable ignition source for the steady-state tests. An ignition was achieved in one test using two match heads, but in all other attempts ignition was not achieved even though the match head was surrounded by flammable mixture. A possible reason for the ignition failures could be the high gas velocities generated in the steady-state tests, resulting in rapid cooling of the burning particles. For the steady-state tests a 1 J chemical ignitor (supplied by Swan Technology Ltd) was used instead. These ignitors are essentially similar to the match heads, but contain a larger amount of pyrotechnic composition and so generate hotter and longer lived burning particles. The ability to ignite the gas mixture will also depend on the size of the burning particles, the larger the particle the more readily will ignition occur. Thus differences in the sizes of the burning particles produced by the two ignition sources could also be factor in explaining the ignition failures.

INSTRUMENTATION

Flow velocities within the enclosure, during the steady-state tests, were measured with an array six air velocity transducers (TSI model 8455) mounted in a plane 4.25 m downstream of the air inlets for the enclosure.

Gas concentrations were measured with an ADC Series 7000 Methane Gas Analyser. The analyser was zeroed with fresh air and spanned with a standard mixture of known methane concentration before each test. For the quiescent tests, gas concentrations were measured at the gas inlet and outlet of the congested gas volume. Nylon tubing was used for the sample lines and switching between the two sample points was done manually.

For the steady-state tests, gas concentrations were measured at up to ten locations in or around the congested volume. Small bore copper tubing (4.5 mm internal bore) was used for the gas sampling probes. This arrangement allowed the gas sampling points to be positioned with a reasonable degree of precision (about ± 5 mm) of the required location. Gas samples were withdrawn through the probes via nylon tubing to a gas sampling sequencer unit (ADC GHU2 Series Multipoint Universal Switching Gas Handling Unit) and then into the infrared gas analyser. The length of the sample lines was kept as short as possible to minimise the transit times of the gas through the sample lines. A sample time of 30 seconds from each probe was found to be long enough to obtain an accurate measurement of the gas concentration, once steady-state conditions had been achieved within the congested gas volume.

For the measurement of the explosion overpressures, up to five Kistler Model 4043A1 piezo-resistive transducers were used, three with a range of 0 to 2 bar absolute and two of 0 to 1 bar absolute. Due to the elevation of the Buxton site the ambient pressures are below 1 bar absolute, allowing the lower range transducers to be used for measuring explosion overpressures of up to 35 mbar. This was adequate for most of the tests carried out.

All five transducers were used for the tests with the 93.1 m^3 enclosure, one mounted in the solid wall of the obstacle cage and four in the enclosure walls. Four transducers were used for the 14.7 m^3 enclosure tests, with one in the solid wall of the cage and three in the enclosure walls.

Thermocouples were used to monitor the air temperature flowing into the enclosure and the air temperature leaving it (ie at the inlet to the fan). To monitor the ignitions a video camera was also mounted inside the enclosure. This allowed video recordings to be made of the ignitions and also was a quick way of confirming that an ignition had occurred.

EXPERIMENTAL PROCEDURE

Two types of ignition test, quiescent and steady-state, were undertaken to investigate the overpressures generated by small partial fills of gas.

Quiescent Tests

For the quiescent tests the congested gas volume was located centrally within the enclosure, ie the geometric centre of the obstacle cage and enclosure were the same. The cage was orientated so that the closed side faced the fan end of the enclosure and the air inlets and outlets to the enclosure were sealed.

To contain the gas mixture, the open sides of the obstacle cage were sealed with polythene sheet (100 micron thick), the sheets being attached to the cage frame using double-sided tape. The enclosed volume was then purged with a stoichiometric methane/air mixture (9.5 $\pm$ 0.2% v/v) until the gas concentration measured at the cage gas outlet was the same as that at the gas inlet. To achieve this the volume of gas mixture used was at least three times the volume of the obstacle cage.

Once the required gas concentration was achieved at the gas outlet, the purging was continued for at least another two minutes before the gas flow was switched off. After a further period of one minute, to allow the gas mixture within the cage to become quiescent and the internal and external pressures to equalise, the mixture was ignited with an electric match head (located at the centre of the metal plate).

Steady-state tests

In the steady-state tests the obstacle cage was always positioned centrally in the cross-section of the enclosure. The distance between the leak source (front face of the critical flow nozzle), however, was changed from test to test. The aim was to achieve a steady-state gas concentration of between 50% LEL and 100% LEL at the edges of the cage. The cage orientation was the same as in the quiescent tests, ie the side closed with the metal plate faced the fan end of the enclosure.

For the steady-state tests the open sides of the obstacle cage were not sealed, gas being allowed to accumulate within the congested volume as a result of air entrainment into the gas jet and jet impingement on the pipe array.

At the start of a test the ventilation fan was switched on and run for at least ten minutes, to allow the airflow through the enclosure to stabilise. The wind strength and direction were also noted. The aim was to undertake tests under conditions of relatively low wind speeds. This was achieved for the majority of the tests carried out. Once the ventilation flow had stabilised, methane release was initiated by opening the pneumatically operated valve on the gas inlet. The test was continued until the gas concentration measurements indicated that steady-state gas concentrations had been established within the congested volume (successive concentration measurements at a given point within $\pm 0.3\%$). In all the tests it was found that steady-state conditions were established in under five minutes. Tests were usually run for 12 to 15 minutes. Note that it took five minutes to cycle through all the ten gas sample positions.

Once steady-state conditions had been achieved the mixture was ignited, either by electric match heads or a chemical igniter. Following a successful ignition of the gas mixture in the congested gas volume, the gas issuing from the critical flow nozzle ignited and burnt as a fierce jet flame. To ensure this flame was rapidly extinguished, to minimise heat damage to the test rig, the gas inlet valve was automatically closed within 5 seconds of the firing button being pressed.

EXPERIMENTAL RESULTS

QUIESCENT TESTS

The quiescent tests were carried out in the two sizes of enclosure, 93.1 m^3 and 14.7 m^3, with the gas cloud located centrally within the enclosure. For the 93.1 m^3 enclosure, tests were carried out with gas cloud volumes equal to 0.098%, 0.55% and 1.07% of the total enclosure volume and for the 14.7 m^3 enclosure with cloud volumes of 0.106% and 0.62%.

Tables 1 and 2 summarise the maximum overpressures measured in each test. The atmospheric pressure recorded for each test is also included in the tables. Pressure transducer PT1 was mounted in the metal plate sealing one side of the cage containing the gas cloud and transducers PT2 to PT5 in the walls of the enclosure. The overpressure-time

Table 1. Summary of maximum overpressures for the 93.1 m^3 enclosure

Test no	Congested volume size (%)	Obstacle Arrangement	Maximum overpressure (mbar) PT1	PT2	PT3	PT4	PT5	Atmospheric pressure (mbar)
JIP006	0.098	None	16.2[(1)]	5.7	5.6	5.6	5.8	972
JIP007		B	14.3[(1)]	6.6	6.3	6.5	6.6	972
JIP001		A	20.3[(1)]	5.6	6.5	7.3	7.4	960
JIP009	0.55	None	33.0	33.9	33.1	32.9	33.2	979
JIP008		B	32.6	32.8	33.0	33.0	33.0	976
JIP010		A	39.1	39.4	39.9	40.6	40.8	979
JIP004	1.07	None	68.4	69.0	67.9	–	–	974
JIP005		B	72.9	72.8	70.9	–	–	972
JIP003		A	77.9	77.6	79.6	–	–	980

[(1)]Maximum overpressure due to the pressure spike attributed to the rupture of the confining plastic sheets

histories obtained for Test JIP010 are given in Figure 3. Figure 4 compares the maximum overpressure measured by transducer PT2 in each test against the theoretical value. The theoretical value was obtained by assuming adiabatic conditions, ie no heat losses to the walls of the enclosure during the explosion.

For a given test the maximum overpressures measured at the different locations are very similar, with the exception of the overpressures measured by PT1 in the tests with the smallest gas clouds. In these cases the maximum overpressure is due to a pressure spike in the pressure-time trace. The reason for the pressure spike is thought to be due to a build-up of pressure in the gas cloud before the plastic sheets retaining the gas are burst. The pressure required to burst the plastic sheets would decrease as the size of the gas cloud

Table 2. Summary of maximum overpressures for the 14.7 m^3 enclosure

Test no	Congested volume size (%)	Obstacle Arrangement	Peak overpressure (mbar) PT1	PT2	PT3	PT4	Atmospheric pressure (mbar)
JIP032	0.106	None	13.6[(1)]	4.4	4.4	4.3	991
JIP033		B	–	4.3	4.5	4.5	969
JIP031		A	10.9[(1)]	4.5	4.7	4.4	991
JIP029	0.62	None	17.6	18.5	18.6	18.5	984
JIP030		B	22.4	22.0	22.6	21.7	987
JIP034		A	33.3	28.2	28.8	28.0	971

[(1)]Maximum overpressure due to the pressure spike attributed to the rupture of the confining plastic sheets

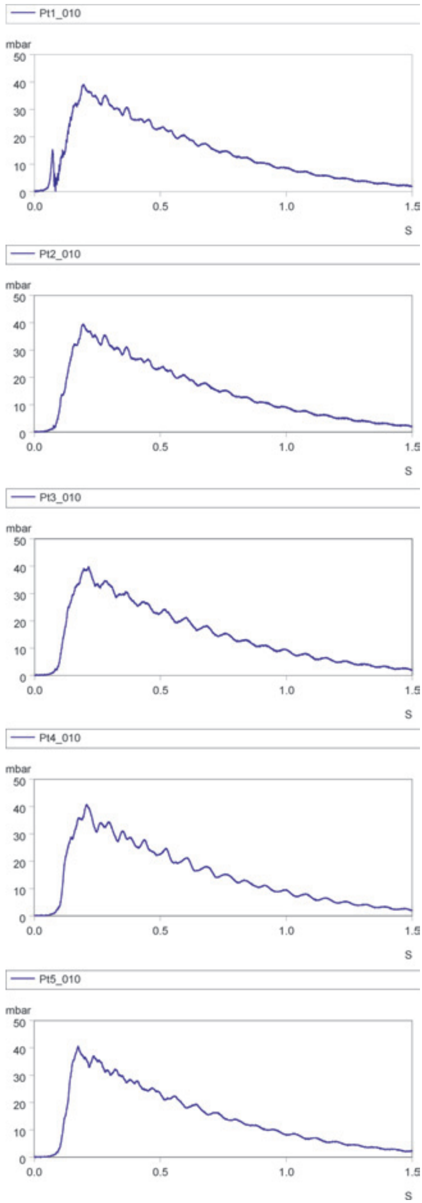

Figure 3. Overpressure-time plots for Test JIP010

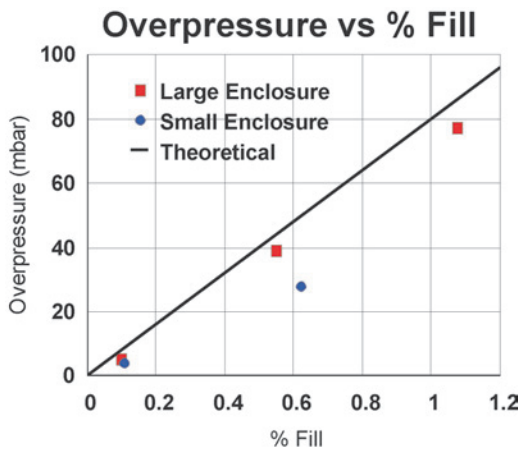

Figure 4. Maximum overpressures vs partial fill of flammable mixture

increased, which would explain why the pressure spike recorded by PT1 for the larger gas clouds did not produce the maximum pressure.

Another effect of confining the gas mixture with plastic sheet would be in the early stages of the explosion, until the sheets burst, to reduce the flow of unburnt gas ahead of the flame front. This would result in slightly lower flame speeds and pressures during the initial stages of the explosion compared to an arrangement, which is not possible to achieve experimentally, of a confining membrane with zero burst pressure.

Examination of the overpressure-time traces for each test showed that a uniform pressure was developed throughout the enclosure, ie the overpressure-time traces recorded by the pressure transducers PT2 to PT5 are essentially identical. The reason being that the time for the pressure wave to travel through the enclosure, the wave propagating at the speed of sound, is very much less than the rise-time of the pressure wave. For very large enclosures this would not be the case and differences in the overpressure-time traces recorded at different locations would be expected.

Tables 1 and 2 show that increasing the level of congestion, from no obstacles to Arrangement A, had little effect on the maximum overpressures generated. Even for the highest level of congestion, obstacle Arrangement A, the maximum overpressures were less than the theoretical values calculated for enclosures partially filled with a stoichiometric methane/air mixture. On the other hand the effect of increasing the level of congestion on the rate of pressure rise was appreciable.

There are also two significant differences in the results obtained with the two sizes of enclosure. For the smaller enclosure the maximum overpressures are about three quarters of the values measured in the larger enclosure and the rates of pressure decay are greater. The lower overpressures are attributed to the greater surface to volume ratio of the smaller enclosure, which would result in higher heat losses and thus lower explosion overpressures. The higher heat losses would also account, at least in part, for the faster rates of pressure decay. The leakage rates from the two sizes of enclosure are also likely to be similar — the bulk of the leakage being from the sealed air inlets and outlets which are common to both sizes of enclosure. Thus with the leakage rates being similar, but the smaller enclosure having a volume of approximately one sixth of the larger enclosure the pressure decay would be much faster in the smaller enclosure.

STEADY-STATE TESTS

The steady-state tests were all undertaken in the larger enclosure (93.1 m^3) and limited to a congested volume of 0.098% of the total enclosure volume. To keep the number of variables in the tests to a minimum the same enclosure ventilation rate and gas leakage rate, nominally 250 $m^3 h^{-1}$ and 0.044 $kg\,s^{-1}$ respectively, were used for all the tests.

The aim in these tests was to achieve a steady-state gas concentration of between 50% LEL and 100% LEL at the edges of the congested volume, by varying the distance between the leak source and the congested gas volume, before igniting the gas cloud. This was not fully achieved in the tests. From the limited number of concentration measurements made outside the congested gas volume, it is estimated that for the conditions used in the tests the volume of the flammable cloud (ie the volume within the 50% LEL iso-surface) was very approximately twice the congested gas volume.

The tests were carried out for two levels of congestion using obstacle Arrangements A and B. The maximum overpressures measured in each test and the atmospheric pressure are summarised in Table 3. The results of the steady-state gas concentration measurements and the overpressure-time histories obtained for test JIP014 are shown in Figures 5 and 6.

Pressure transducer PT1 recorded much higher maximum overpressures than the transducers mounted in the enclosure walls and the maximum also occurred at a much later time. It is thought that the maximum overpressure recorded by PT1 is as a result of heating of the transducer and not the explosion. Following an ignition a jet flame was established at the leak source, which would have impinged on PT1, and continued to burn until the gas supply was turned off.

Table 3. Summary of maximum overpressures from the ignition tests

Test no	Congested volume size (%)	Obstacle Arrangement	Maximum overpressure (mbar)					Atmospheric pressure (mbar)
			PT1	PT2	PT3	PT4	PT5	
JIP014	0.098	A	20.8(1)	11.3	10.8	11.2	10.8	968
JIP026		B	21.3(1)	10.5	10.8	11.3	11.3	971
JIP027		A	18.5(1)	10.4	10.7	11.8	10.1	966

(1)Maximum overpressure due to thermal effects on the pressure transducer

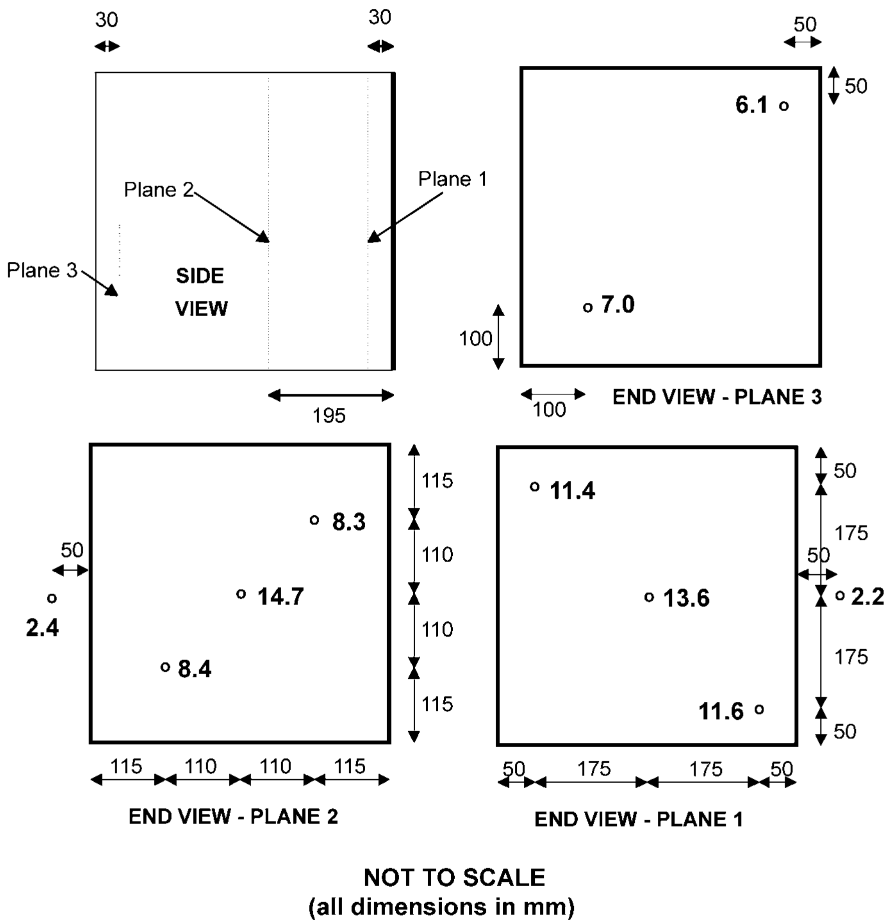

Figure 5. Steady-state gas concentrations (% v/v) for test JIP014

The shapes of the pressure waves generated in the steady-state tests are different from those generated in the quiescent tests for the 93.1 m^3 enclosure and 0.098% congested volume. Two pressure peaks are exhibited in the pressure traces from transducers PT2, PT3 and PT4, the separation of the peaks increasing as the measuring point moves closer to the air inlets in the enclosure (see Figure 6). Traces from PT5, located towards the air outlets, show only one peak, but it is very broad and could be due to the coalescence of two peaks. The reason for this double peak structure is not clear, but one possible

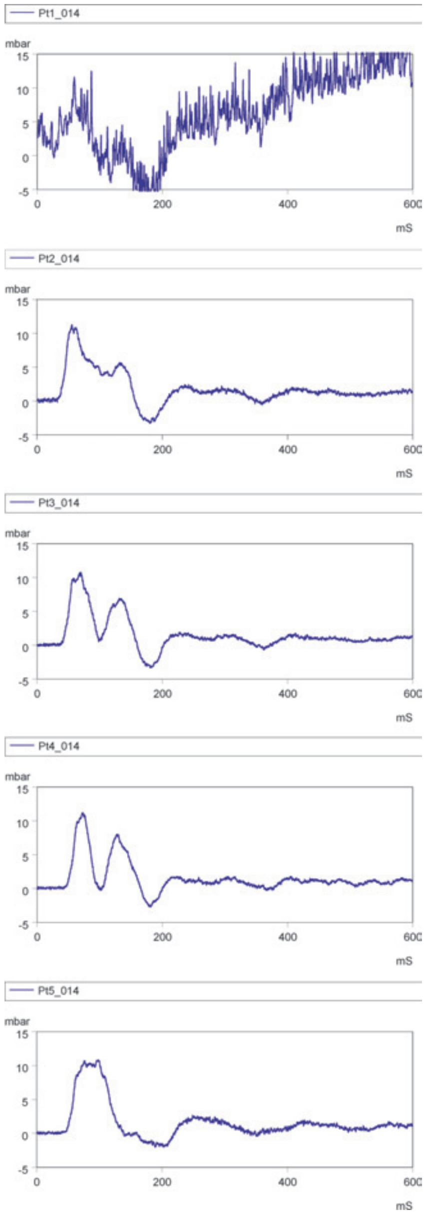

Figure 6. Overpressure-time plots for Test JIP014

explanation is that it is due to the ignition of gas outside the congested volume. This would be similar to the external explosion observed in explosions in vented enclosures[6]. The faster rates of pressure decay seen in the steady-state tests compared to the quiescent tests are probably due to venting of the explosion through the air inlet and outlet openings.

That very similar maximum overpressures were obtained for obstacle Arrangements A and B, suggests that under the conditions that applied in the ignition tests the turbulence generated by the jet, rather than the turbulence generated by the obstacles, determined the explosion magnitude. In some practical situations, where the gas accumulates in a congested volume away from the source of the leak, the obstacle-generated turbulence is likely to be the controlling factor.

It should be noted that in these steady-state ignition tests, unlike the quiescent tests, that the enclosure was not sealed. The air inlets and outlets would act as explosion vents and provide some explosion relief, resulting in a reduction in the maximum explosion overpressures.

CONCLUSIONS

Ignition tests have been carried out in two sizes of enclosure, 14.7 m^3 and 93.1 m^3, with gas clouds of homogeneous and quiescent stoichiometric methane/air mixture ranging in size from about 0.1% to 1% of the total enclosure volume.

Ignition of the quiescent clouds resulted in the generation of a uniform pressure field throughout the enclosure.

Increasing the level of congestion within the quiescent cloud resulted in a small increase in the maximum explosion overpressures generated, but a significant increase in the rate of pressure rise.

The maximum overpressures generated, even for the highest congestion levels, were always less than the calculated values for partial fills of a stoichiometric gas mixture. Comparison of the results from the two sizes of enclosure suggested that pressures approached the theoretical value as the size of the enclosure and thus the absolute size of the gas cloud increased.

Ignition tests have also been undertaken for a steady-state gas cloud, produced by a high pressure gas leak into a congested region inside a 93.1 m^3 enclosure. The enclosure was force ventilated and the congested region was approximately 0.1% of the total enclosure volume.

The maximum overpressures measured on ignition of the steady-state gas cloud, if allowance is made for the gas mixture accumulating outside the congested region, were comparable with those obtained in the quiescent ignition tests.

Changing the level of congestion in the steady-state ignition tests had negligible effect on the maximum overpressure or the rate of pressure rise. This suggests that under the conditions used in the tests the turbulence generated by the gas leak, rather than the turbulence generated by explosion induced gas flow over the obstacles, was the main factor in determining the magnitude of the explosion.

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