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Porous Media Combustors for Clean Gas Turbine Engines

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Abstract

A preliminary assessment has been made of a combustor in which the reaction is stabilized in a porous, incombustible medium. Its performance at elevated pressures and inlet temperatures has been studied, with emissions and stability determined over a wide range of conditions, together with the pressure loss and diffusivity of the porous matrix elements from which the combustor is made. The combustor was formed of reticulated porous ceramics, untreated to augment or sustain chemical reaction. The characteristics of combustion within porous media which are attractive in a propulsion context are the ability to burn leaner and hotter than a free flame, with low emissions, no cooling requirement for the combustor itself and the potential to operate free from combustion-induced noise. The reduced combustion loading resulting from lean burn operation is partially offset by heat transferred within the porous matrix raising the maximum reaction temperature. Data has been obtained at pressures to 1200kPa, reactant preheat to 700K, with methane, methane-hydrogen mixtures and hydrogen alone. The results show that the combustor operates in a "super-adiabatic" mode, with low emissions. Intrinsic pressure loss is within values commonly accepted for propulsion gas turbines. No durability problems were found, within operating durations of ~40hours per matrix assembly.

The study has advanced knowledge of combustion in porous media and its applicability to propulsion systems, particularly gas turbines. The performance at elevated pressures and inlet temperatures for lean mixtures has not been studied previously.

The experimental studies have been compared to results from computations made in a companion study by Professor Janet Ellzey's group at the University of Texas at Austin (Contract N00014-01-1-0207). Visiting students from Austin and Ecole Centrale de Nantes also assisted with some of the work. Four US students visited Cranfield University over two summer periods. The other two were involved as part of the separately-funded, on-going research of the Cranfield group, which was relevant to this study.

Component design of any propulsion combustor is a composite subject covering mechanical sizing, thermofluid, thermal and material performance and manufacturability of the finished device, all integrated, and drawn against a performance specification and installation envelope. In this report, specific elements of this spectrum only are considered for a porous matrix combustor where the combustion reaction occurs *intentionally only within* an assembly of porous elements comprising the main combustor envelope. The objective is *not* to exploit the purely homogeneous phase reactions downstream of the matrix assembly or a surface-stabilized flame and the experiments have been so constructed and run to preclude these features. The report focuses primarily on the combustion characteristics of the burner but includes some observations on materials and thermofluid aspects.

Progress of the work was presented at a series of ONR Propulsion Conferences over its duration and written reports submitted annually or as

requested by the ONR Program Officer. The meetings and involvement with others in the Propulsion Group in ONR has been stimulating and the NICOP involvement has been invaluable to the project. The opportunity to work with Professor Ellzey's group at Austin has been a most pleasant experience, expanding the scope and usefulness of the study.

A summary of the work was presented at the ONR-initiated International Colloquium on Combustion & Noise Control at Cranfield in August 2003. Other open-domain publications are in preparation and agreement to publish will be sought, with full acknowledgement of the ONR support.

Key words: Combustion; Porous Media; Propulsion; Emissions; Fuels.

Introduction

Combustion of a pre-mixed fuel:air mixture within porous media has demonstrated stable operation over a wide mixture range with low emissions at atmospheric conditions, relative to the performance of a free flame. Porous matrix burners consist of a foam or fibre matrix, generally ceramic, fed with premixed reactants. Treating the media to promote or enhance combustion is not necessary to achieve combustion. Reaction occurs within the pores of the matrix and its characteristics differ substantially from a free flame in that the burning speeds are higher and the flammability limits are wider. In addition, the temperature may exceed the inlet reactant adiabatic flame temperature resulting in "super-adiabatic combustion". These features arise from the internal feedback of heat from the combustion zone to the incoming mixture via radiation and conduction from the porous soild.

Early studies on burners having two close-coupled sections of reticulated foam of different pore sizes *with the combustion established at the interface and continuing in the downstream, coarse pore section* have shown wide operating range, multi-fuel capability and low pollutant emissions at atmospheric conditions, [1-4]. The reason for using two pore sizes is to inhibit flame propagation upstream and make the process safer and more flexible. The combustion characteristics of any type of porous matrix combustor have not been studied extensively at elevated pressures, but its properties of stable operation at lean equivalence ratios, low emissions, and relative freedom in geometric design offer attractions for gas turbines and other propulsion engines, especially those where conventional turbulent flame designs may involve small sizes and unconventional shapes.

Flames can also be formed on the surface of porous media, with some of the same attributes of wide equivalence ratio operation and fuel flexibility [e.g. 5]. In these, the input heat is transmitted by conduction in and radiation from the surface layer adjacent to the flame reaction zone in free space. Surface-supported burners are often made using fibrous media but have some limitations, particularly in operating range, where the flame may be more readily blown off than when the combustion is submerged.

Porous media burners applied to gas turbines

The design principles for low emissions turbulent flame gas turbine combustors are well established. The preferred strategy remains lean burn, often with staging to widen the operating range and ignition capability of the combustor. Ideally, the first or pilot stage combustor should possess characteristics of easy ignition, low emissions, and a wide operating range over the entire engine envelope from cranking and light-off to full power. This is not simple to accomplish, especially in cases where retrofit of a new low emissions combustor is desired into existing casing geometries. Constraints imposed by the amounts of air available to aerodynamically control the entire combustion process and cool the combustor make pilot stage design demanding, despite the smaller fraction of fuel burnt in it compared to the main combustor. As the operating equivalence ratio is reduced and as pressure is increased, flame speeds drop. As an example, for methane at an equivalence ratio of 0.6 – the leanest for which free-flame data is available – flame speeds at 0.9MPa are ~1/4 of the value at atmospheric pressure (0.03 c.f. 0.113 m/s), [6]. This has some key effects on the aerodynamically-stabilized combustor: its stability margin and combustion loading reduce significantly and it may suffer from combustion-induced acoustic oscillations large enough to damage components, including the combustor and turbine.

Confining the combustion process within a matrix material reduces the propensity for acoustic oscillation to be generated by altering the feedback mechanism and, if the effective combustion loading is less affected as a result of the 'super-adiabaticity' of the process, the impact on overall combustor sizing may be reduced. Low equivalence ratio operation at typical lean-burn values, 0.4<ER<0.6, has been well-demonstrated for porous burners at atmospheric pressure. The porous media burner requires no wall cooling of the combustion stage as its ceramic materials of choice have softening points around 1600C: indeed, cooling that portion of the burner is a disadvantage as it retards combustion reactions and rate and may lead to poor emissions and flame extinction. The media can act as a distributor for the reactants and this may simplify the fuel preparation stage of the combustor. In addition, the distribution of heat along temperature gradients that are not parallel to the main flow direction aids uniformity of the exhaust gas temperature, another potential benefit of the technique. Thus, although there are several attractive intrinsic properties possessed by the porous burner concept, its combustion intensity, heat release per unit volume, general performance and characteristics at typical propulsion cycle conditions are not known from previous work.

In this project, a preliminary assessment of a model combustor in which the reaction is stabilized in a porous medium has been made by studying its performance at elevated pressures and inlet temperatures. Combustion loading, emissions and stability have been determined over a wide range of conditions. The model combustor is cylindrical and constructed to be quasi-adiabatic, permitting results to be extrapolated on the frontal area of the unit.

Brief summary of previous work on porous media burners

The idea of superadiabatic combustion was proposed by various researchers [7-9] who demonstrated theoretically that temperatures higher than the nominal adiabatic flame temperature could be achieved if heat were recirculated from the hot products to the incoming reactants. The theoretical work was extended [10] to show that a porous solid could provide the necessary heat feedback, and that the flame speed was significantly higher than that of a free flame at the same equivalence ratio. These results were confirmed in later experimental studies in which a flame was stabilized within a tube bundle [11]. Radiation through the porous matrix has been shown to be important to the heat recirculation [12] and hence radiative properties have a significant influence on the flame speed and flammability limit [13].

For most practical applications such as radiant burners, the flame must be stabilized by some means at a fixed location or within a fixed region. Several fundamental studies, however, have been conducted on flames propagating through porous beds without any means of stabilization. These studies have also shown extended flammability limits and enhanced flame speeds [14]. Babkin et al. [15] studied a flame propagating through porous beds fabricated from different materials and with different pore geometries, for pressures ranging from 1 to 25 atm. Their results showed that flame speed is strongly dependent on pressure at equivalence ratios near 1.0 but is only weakly dependent for values near 0.7. Leaner mixtures were not evaluated. Flame speed was also significantly affected by porous media characteristics such as pore geometry and pore size.

Flames formed on the surface of porous media have some of the same attributes of wide equivalence ratio operation and fuel flexibility [4]. Such burners are often made with fibrous media but have some limitations, particularly in operating range and intensity, and the flame may be more readily blown off than when the combustion is submerged.

Computational studies of combustion in porous media have included both single step chemistry [16, 17] and multi-step [18, 19 & 20] and, in general, have confirmed the importance of the porous media properties to the flame behaviour. In particular, the predictions of Henneke and Ellzey [20] showed very good comparison to experimental temperature profiles and reaction front velocities for very lean methane/air mixtures.

Stated objectives and interactions

In the project proposal, evaluation of the overall performance of a porous matrix burner at elevated pressures and inlet temperatures was proposed, primarily in terms of combustion stability and loading and emissions. Various porous media would be studied to arrive at a suitable configuration for a model combustor. Operation was foreseen to maximum target inlet conditions of 18bar, 700K, with fuels including natural gas and other hydrocarbons over a range of equivalence ratios. The study was aimed at performance characterization, an understanding of porosity effects and operational issues such as pressure loss and ignition. Measurements were expected to include in-bed temperature measurements, exhaust gas composition & temperature and broadband radiant emission from the downstream face of the matrix. Liquid fuels would be used if possible.

The experiments would couple with and validate computational aspects proposed as a companion study, extending the work of Henneke and Ellzey by considering reduced mechanisms and elevated pressures and inlet temperatures. The computational studies would also aim to reveal the relative importance of the porous media parameters and help determine their optimum characteristics. The companion study has been reported elsewhere.

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Technical Programme

General Features

Two combustion experiments and one room temperature experiment without combustion have been constructed. The two combustion experiments are aimed primarily at different uses, one operating at atmospheric pressure for exploratory ignition work and one for general high pressure use. Both are configured around porous elements that are 50.8mm diameter and length, enclosed in an alumina tube to provide a quasi-adiabatic, one-dimensional enclosure. These were the maximum sizes of matrix available at the time. Matrix material came from Porvair (Selee Corporation) and the alumina tube from Zircar Inc. The porous materials used have been either Partially Stabilised Zirconia, PSZ, or Yttria Stabilised Alumina, YZA. The combustor contains coarse and fine elements in the same material. YZA material was used throughout for the data reported here: it has a softening point of 1600C and was found to be the most durable of the ceramics available as reticulated porous structures. The softening point fixed the maximum equivalence ratio (ER) to which the combustor was exposed: for methane fuel this represented an ER of ~0.73. The arrangement of the elements puts the fine pore material at the inlet, with the downstream coarse pore matrix abutting it. Figure 1 depicts typical materials used. The number PPI or PPC, pores per inch or cm, is the average number of pores observed in one inch length. The maximum use temperature of the alumina is 1650C.

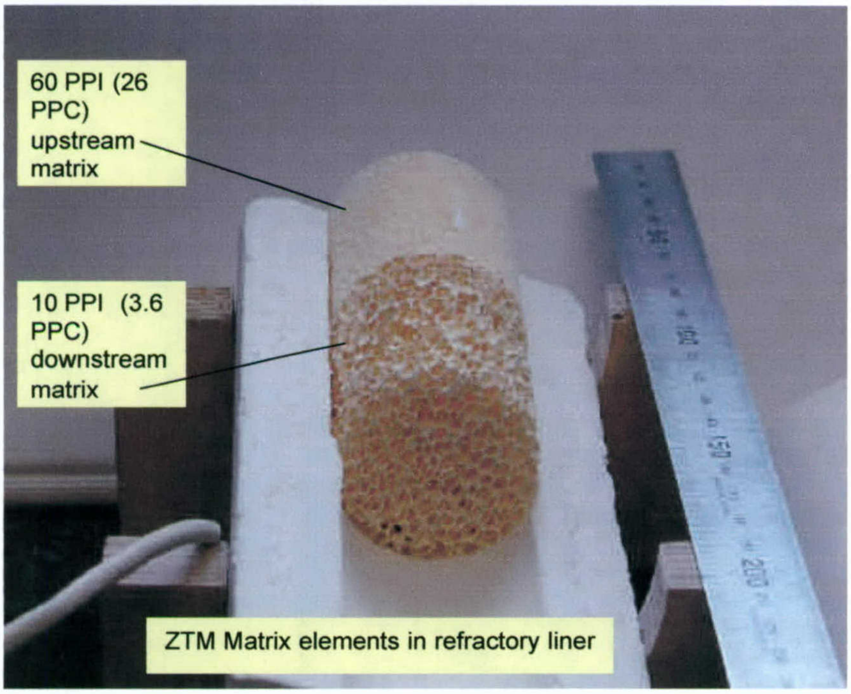


Figure 1 Matrix Elements and Alumina Containment.

Figure 2 illustrates the typical internal arrangement of the high-pressure experiment, with the main features of the fuel/air injection mixer and instrumentation. For some of the work, two sections of coarse pore material were used with the intention of extending the volume in which the reaction could be contained. The alumina tube was split to facilitate assembly – the elements were a tight fit in it, providing adequate pressure sealing when assembled – and the tube was mounted into its steel containment using intumescent mat.

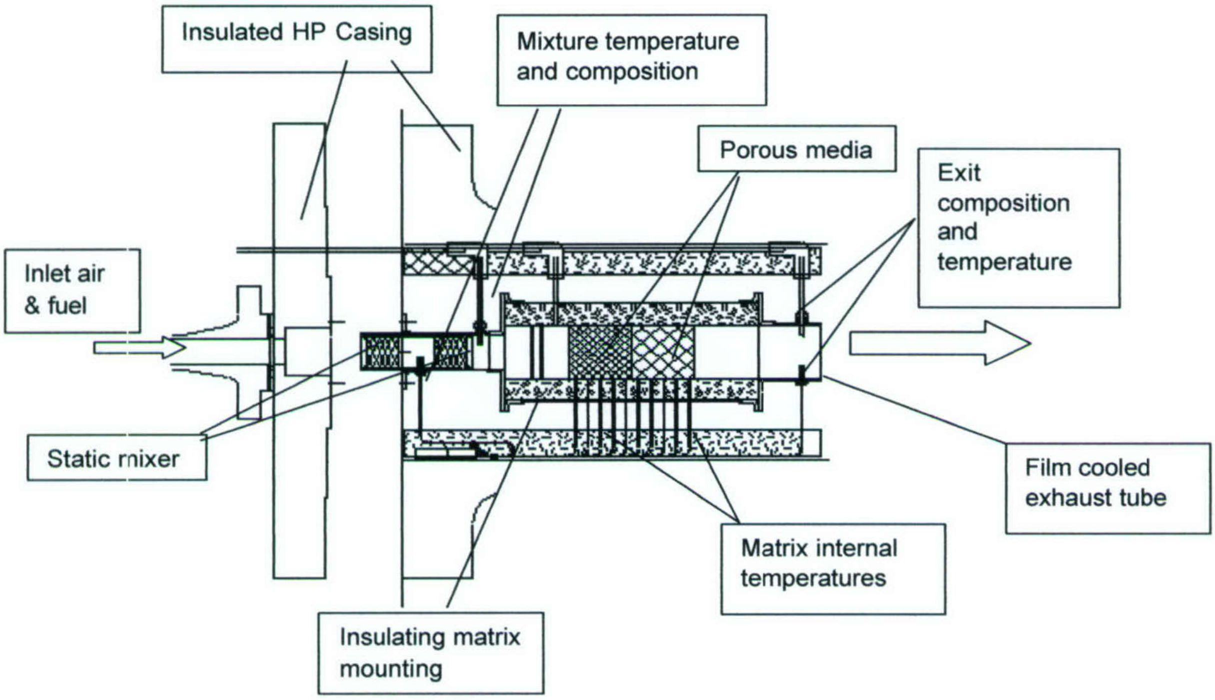


Figure 2 Typical Internal Arrangement of the High Pressure Experiment.

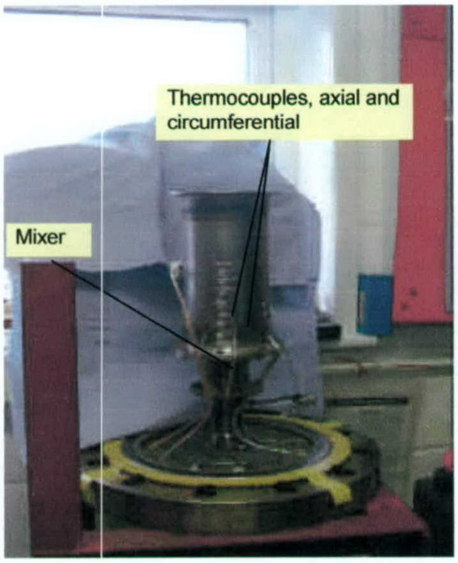


Figure 3a Combustor Matrix Assembly, Prior to Installation on HP Casing Flange

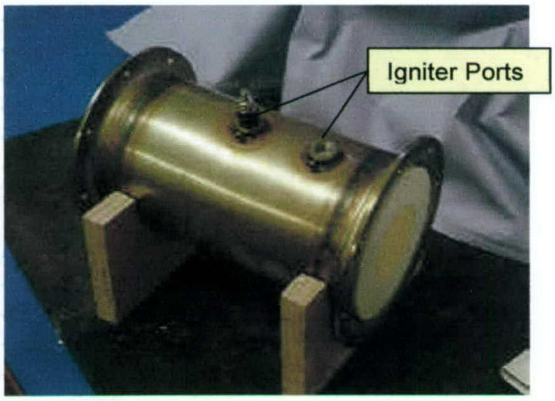


Figure 3b Typical Matrix Assembly for all Experiments, showing Alternative Igniter Mounting Points

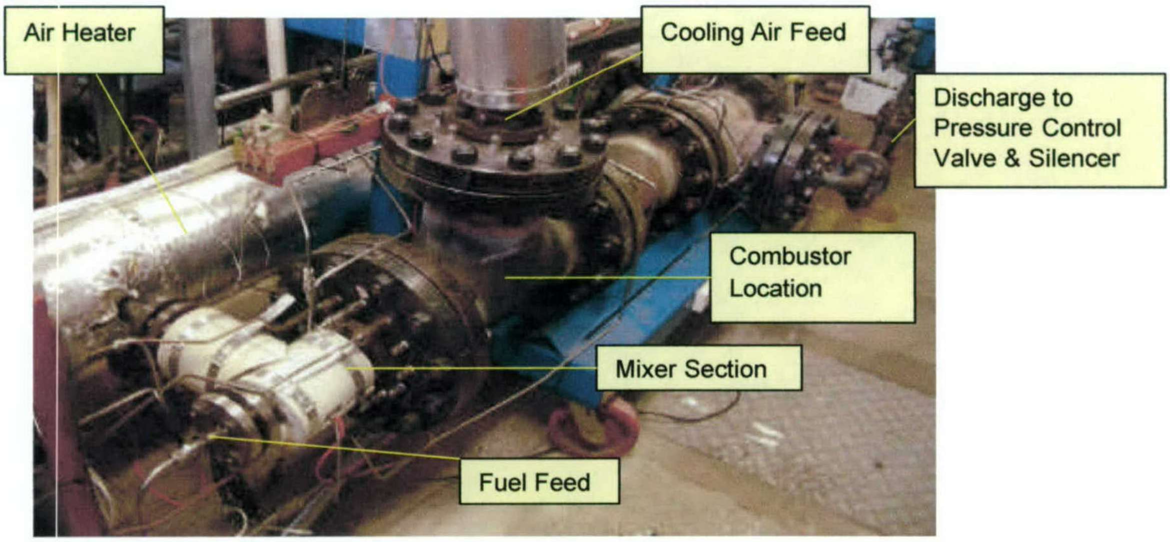


Figure 4 High Pressure Combustor Stand.

Design Considerations

It was known form other work that the radiant heat loss from the end faces of a monolithic combustor can significantly affect its reaction performance. As part of the design process for the experiments, a design study was carried out by the first two UT students, Elverum & Mathis. This covered instrumentation, component scantlings and assessment of the cooling needs of the combustor, its thermal losses and means of mitigating them. In a combustor of the size used, the effects of uncontrolled heat loss can be profoundly misleading and have an important effect on the quality of the results. As the combustor size was conditioned by the matrix elements available, care was necessary. The cooling design produced a film-cooled discharge tube to carry the exhaust gas from the matrix elements and to attemperate the exhaust gas to a level that would quench the reaction, simplifying gas analysis, and represent a typical value to an expansion turbine. Control of the radiative loss was accomplished by extending the sintered alumina mounting tube one to two tube internal diameters beyond the downstream face of the coarse pore element, thus controlling radiative losses to the colder parts of the high pressure containment: this offered an optimum solution, given other component considerations. Radiative losses for the arrangement were estimated by the 'View Factor' method, with some assumed material properties for the containment and matrix materials, coupled with equilibrium estimates for the maximum combustion temperature. The convective/conductive losses through the 'adiabatic' containment were estimated using the conductivity of the enclosure materials, coupled with a mid-thickness temperature measurement in the alumina liner, via a simple zone model. With a combustion rate of 2kW, typical of atmospheric pressure operation and operating temperature, the radiative loss was estimated to be 80W (~5%) and the conductive loss 86W, using manufacturer's temperature-dependent material property data. At the highest firing rates (~10kW) the total losses were ~ 150W. The combustor loading scales directly with pressure and ER:

the temperatures are constrained to material limits by the manner of operation.

Reactant Supplies

Reactants for both experiments were fed from a multi-stream, PC-controlled fuel system, shown in Figure 5. It contains thermal mass flow controllers for fuel feed metering and control from HP cylinders and Coriolis meters for the higher air flow rate measurements. In the case of the high-pressure experiments, air was provided from two sources, combustion air from HP cylinder packs for the combustion process and a larger flow for cooling from two separate small compressors (35bar) for the coolant flows, permitting independent adjustment. The air supply may be heated on demand. The exhaust from the HP combustor was further attemperated by water injection before being discharged to waste through the rig pressure-maintaining valve, via a silencer.

Three gaseous fuels have been studied, methane, methane/hydrogen and hydrogen. The intention of using vaporized liquid fuels was frustrated by a major fault on the vaporizer which could not be cured within the time available and hydrogen was substituted as a fuel having propulsion application. The results are considered to be generally applicable to higher hydrocarbons, however.

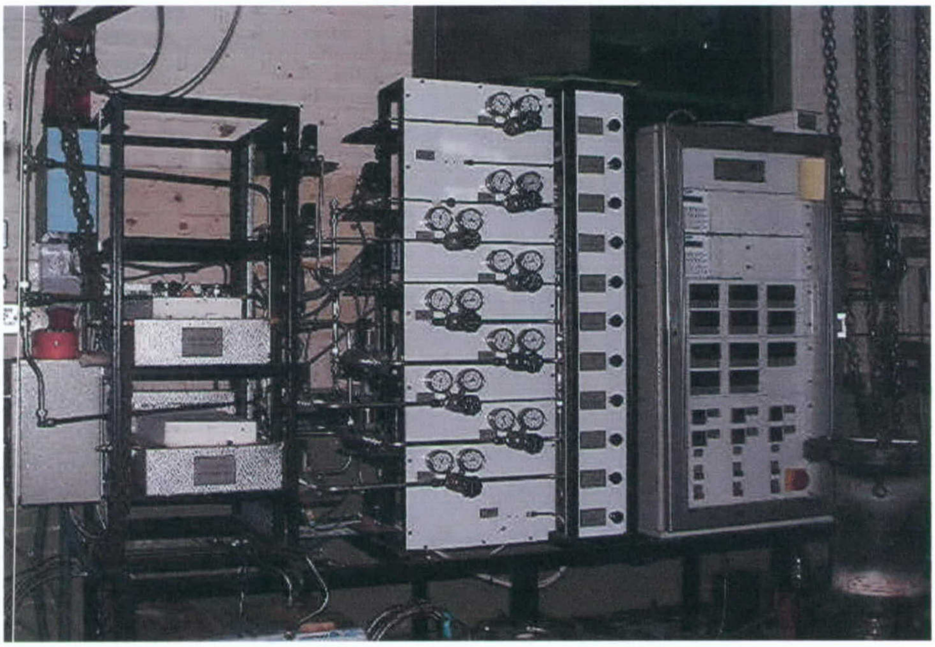


Figure 5 The Gas Forwarding Station.

The complete high pressure rig stand system diagram is shown in Figure 6. Some of the features were not used during these experiments and the fuels used were simple compounds, rather than stream-blended.

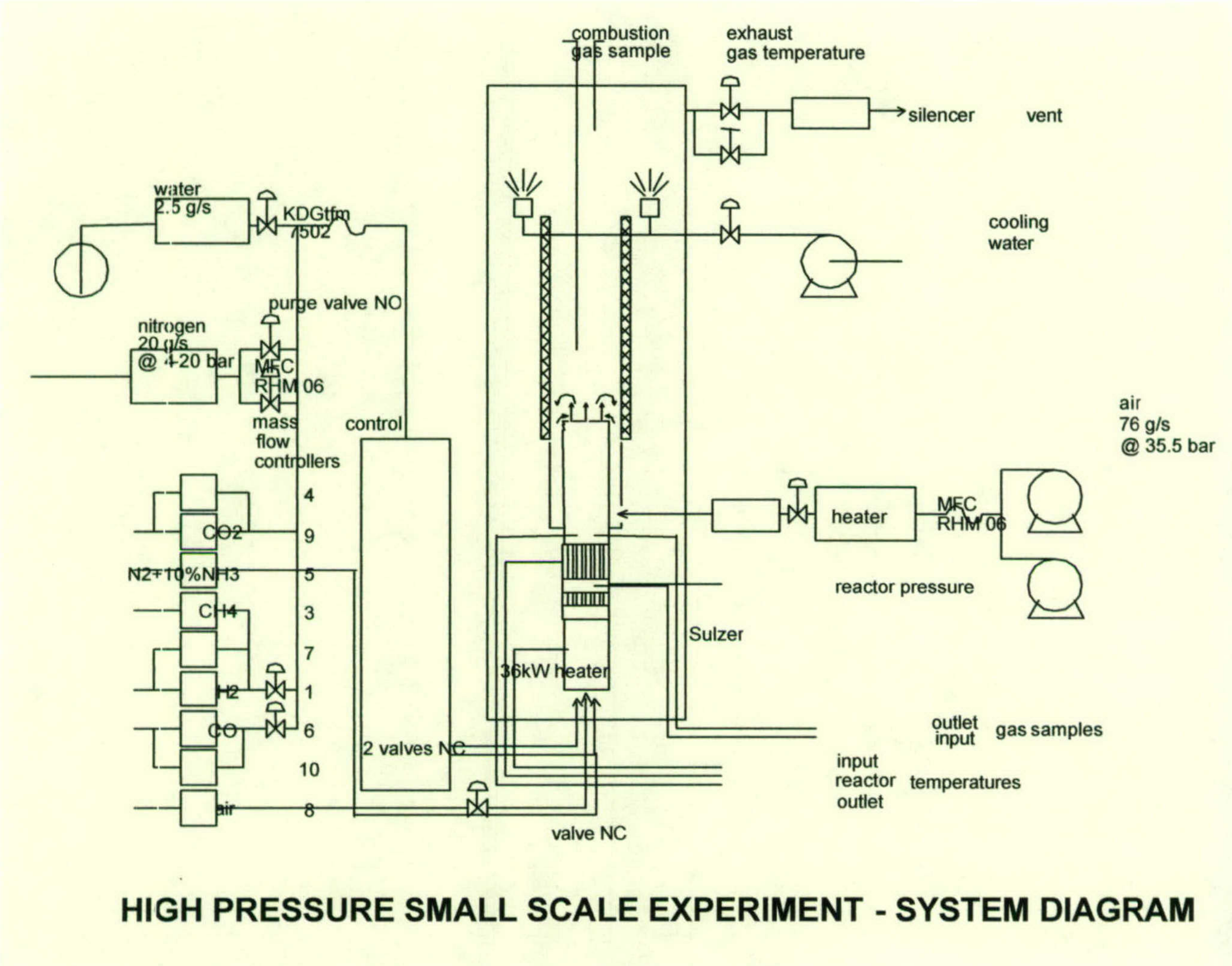


Figure 6 High Pressure Rig Stand Schematic Arrangement.

Instrumentation & Data Acquisition

Measurements were made with pressure transducers and thermocouples, in addition to the thermal mass flow meter/controllers. Calibrations were checked at 6-monthly intervals for pressure transducers and traceable, preformed thermocouples were used, with National Standard certification for temperature. The mass flow controllers were calibrated against sonic orifice meters, which are themselves made to British Standard 1042 and checked on a positive displacement bell prover. The entire data acquisition string is incorporated in the calibration, from sensor to display/logger. Secondary standards for pressure and voltage injection (t/cs) are used to simulate input signals. The uncertainty in logged data does not exceed 2%.

The data is acquired to PC via standard logging chassis, with 12bit A-D conversion. It comprises: inlet mixture flows, temperatures and pressures; mixed gas temperature and pressure to the combustor. Matrix temperatures are taken at various positions in the matrix using 1mm diameter type N, R or

B sheathed grounded-junction thermocouples according to expected temperature. Thermocouple measurements are handled in the PC by NBS or equivalent characteristics or look-up tables, according to thermocouple type. The thermocouple layout for the 2- and 3- matrix builds is shown schematically in Figure 8. The nature of the ceramic matrices precluded precise positioning for insertion depth and axial location of the sheathed thermocouples, but the data is self-consistent per build and the positions are accurate to <1mm. The mounting method was to drill small holes in the stainless steel mounting can, alumina liner and matrix and fix the thermocouples into position with ceramic cement at the joint interfaces to seal and fix their position – Figure 3a. The low fluid velocities and predominant radiant enclosure characteristics in the matrix are assumed to yield cavity wall temperature, i.e. that of the solid medium. The conduction along the thermocouple is assumed to be small: 1mm diameter sheathed elements were used and even with a full array of ~10 buried elements the total (composite material) cross-section is less than 0.5% of the active combustor section.

Exit gas composition is given from calibrated species-dedicated analysers. CO_2 and CO are measured using non-dispersive infra-red methods; NO_x by chemiluminescence; UHC by flame ionization, calibrated with either methane or propane, depending on the C/H ratio of the fuel, and Oxygen by the paramagnetic method. Alpha-standard gases were used to calibrate analysers, with check span, and zero confirmed before each trial and similar methods used from signal to data, as described above. Gas samples are quenched in the water-cooled sample extraction probe. Results are reported uncorrected for oxygen content and dry, unless otherwise stated. The gas analysis apparatus is shown in Figure 7.

Selected data is converted to engineering units and output to the PC to provide an operator interface when running experiments. Data was manipulated off-line in EXCEL.

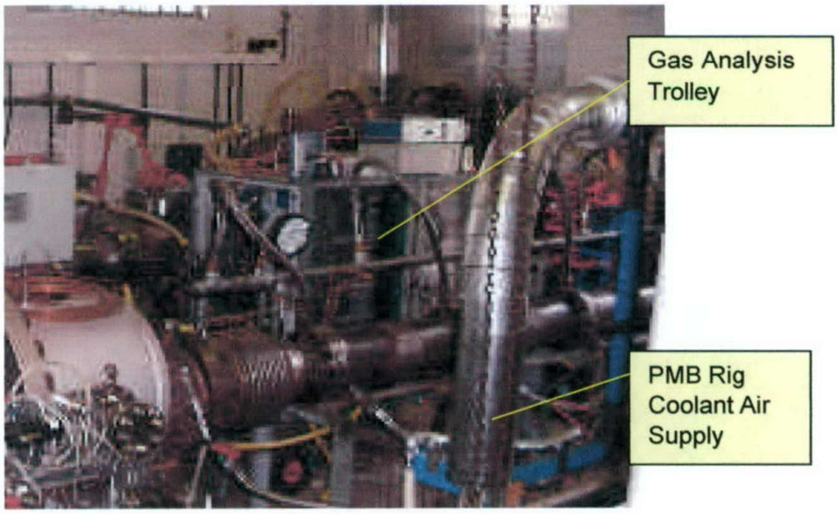
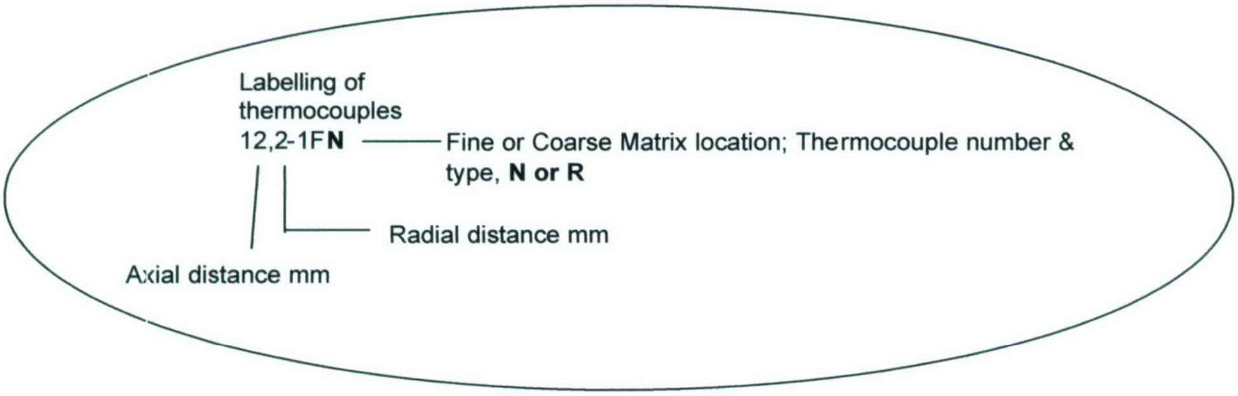


Figure 7 Gas Analysis Apparatus.



Thermocouple Identification

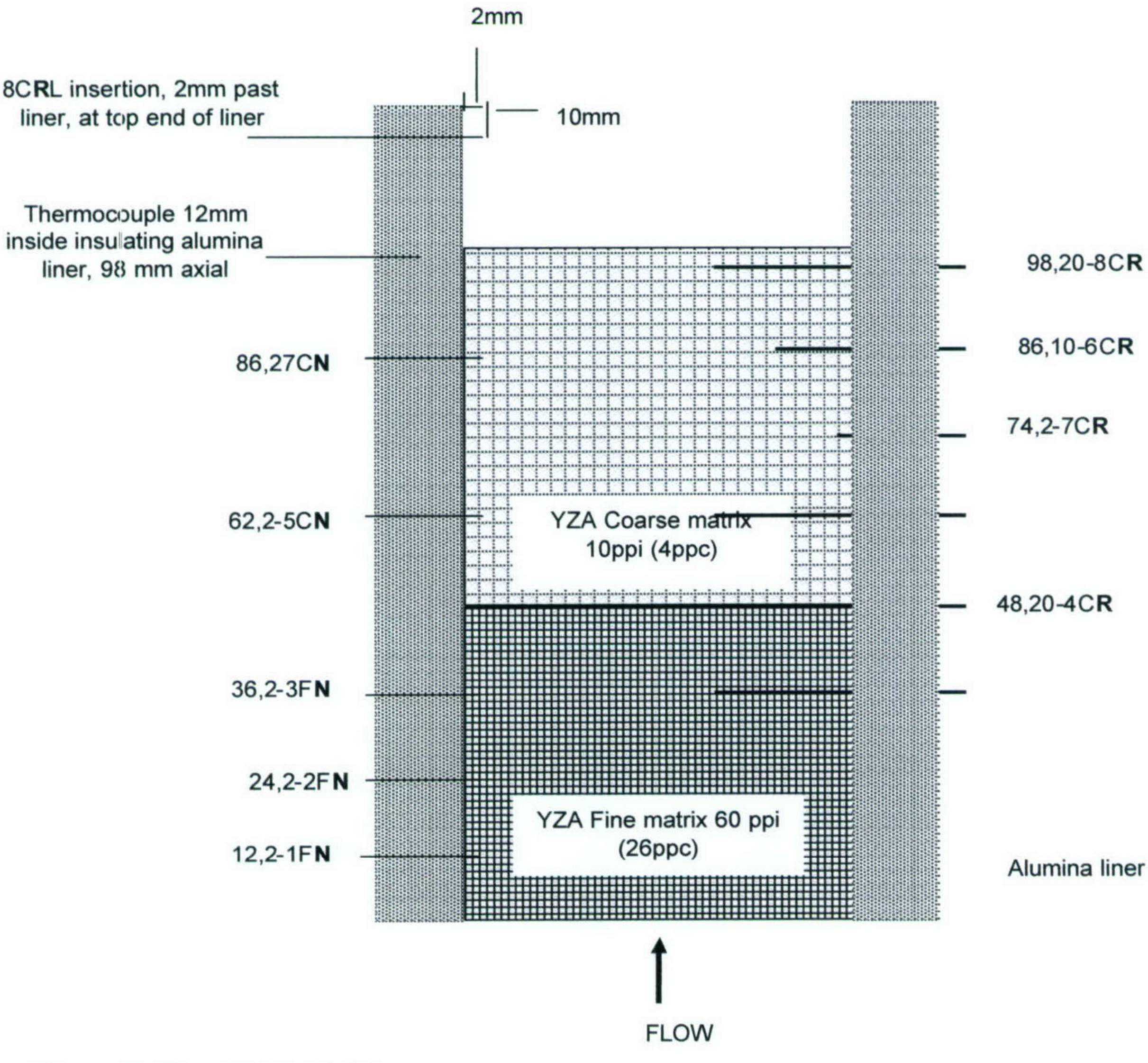


Figure 8a Two-Matrix Build

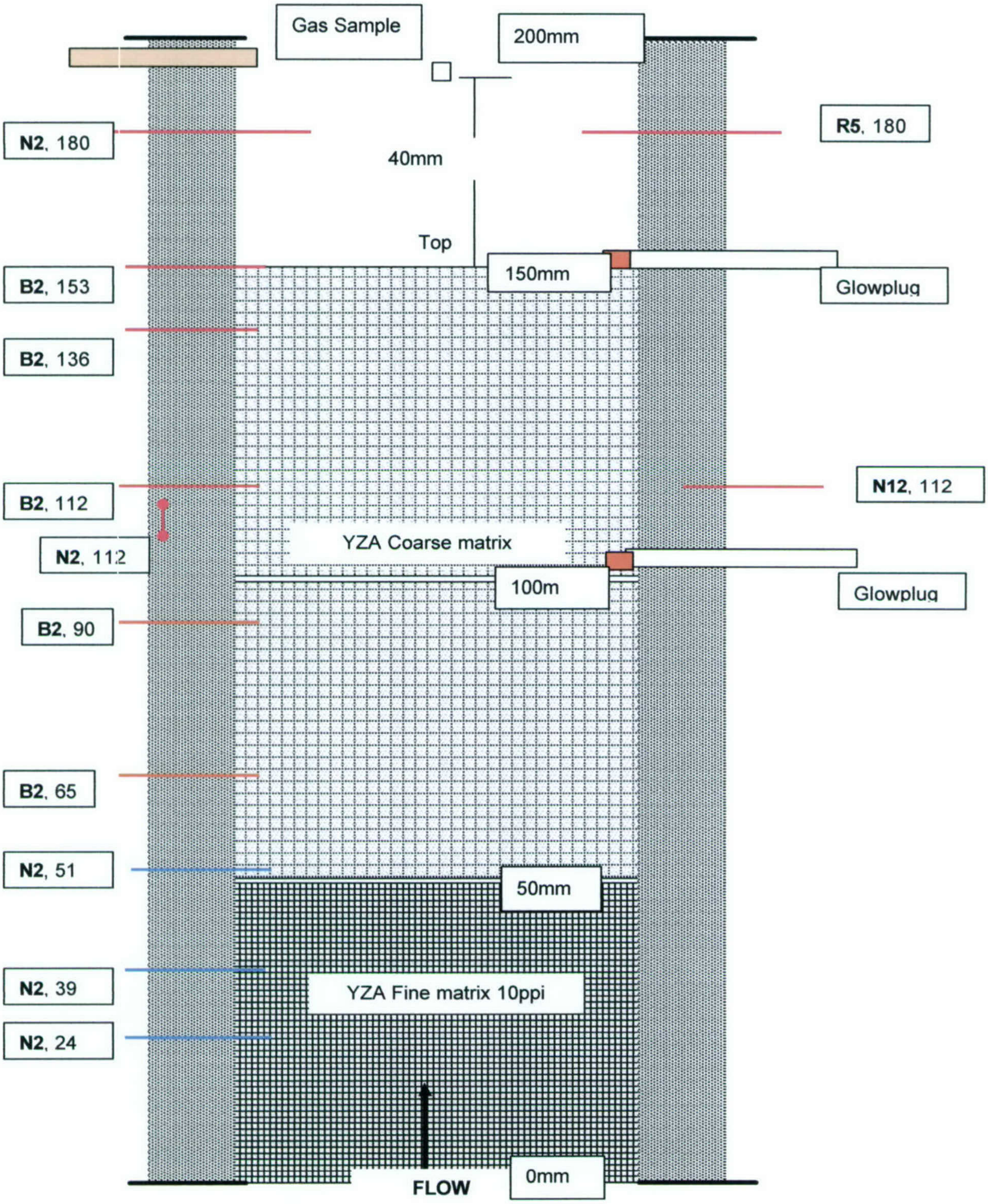


Figure 8b Three-Matrix Build

Figure 8 Thermocouple Layout & Nomenclature for the High Pressure Experiments with Two- and Three- Matrix Assemblies.

Ignition Experiments

The ignition experiment is similar to the high-pressure one in layout, assembly and instrumentation but has a different fuel injection system to permit radial variations in mixture profile to be applied if required. Different flow conditioning was applied to the air:fuel mixture to preserve applied mixture non-uniformities. The air heater was integral with the casing in this apparatus. Figure 9 illustrates the unit.

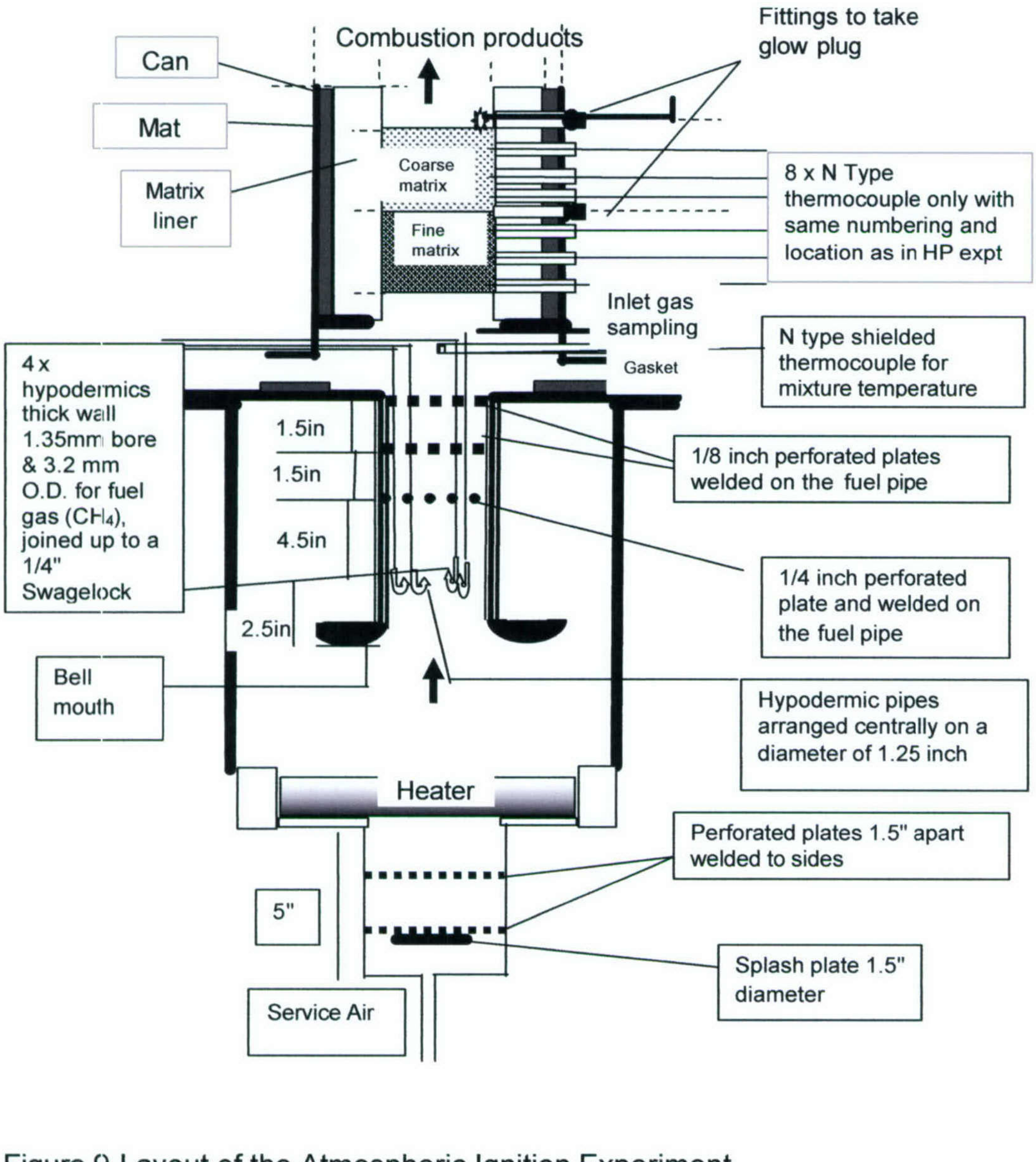


Figure 9 Layout of the Atmospheric Ignition Experiment

Four ignition devices were used in the studies, shown in Figure 10. They were a plain resistive wire, an alumina-encapsulated resistance heater; a miniature glow-plug used in model aircraft and a hot-tip automotive diesel glow-plug. All could be run from low-voltage DC batteries, either 9 or 12volt.

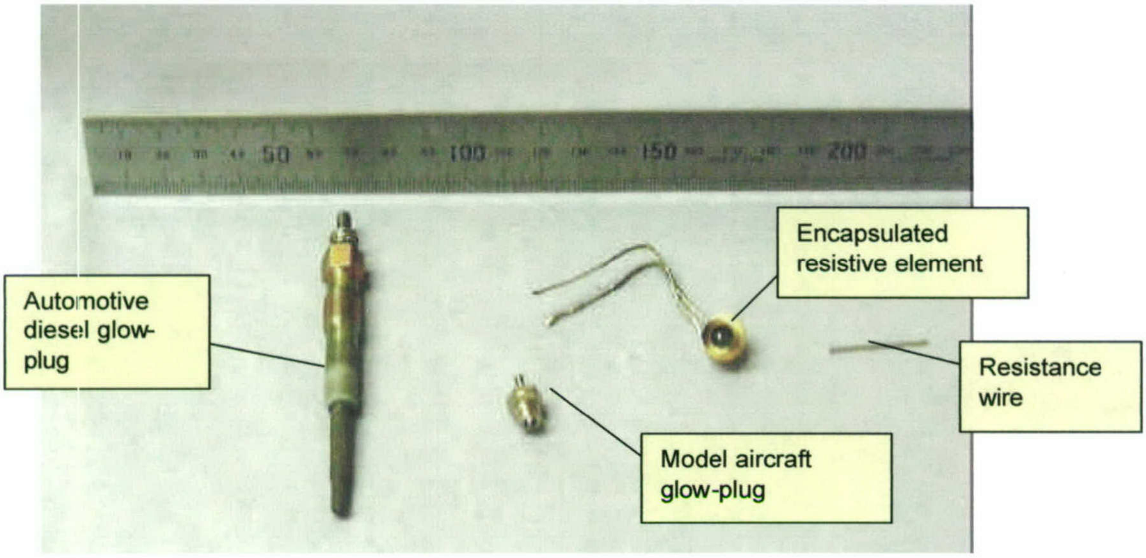


Figure 10 Ignition Devices Trialled.

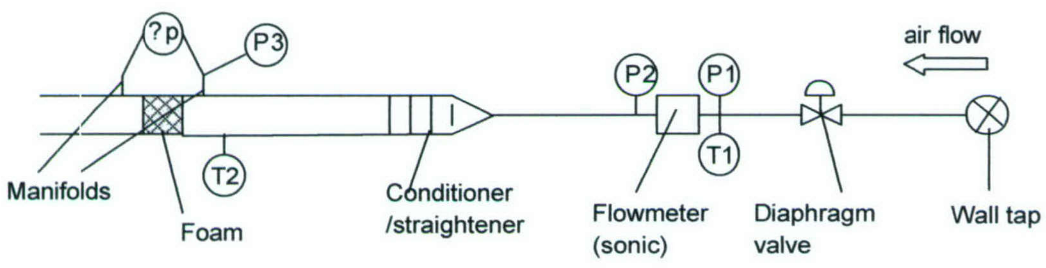
During the work, ignition studies were performed in the HP rig with an additional coarse pore matrix butted up to the first coarse pore stage. The glowplug locations are shown in Figure 8b.

Isothermal Measurements: Pressure Loss & Scalar Dispersion

An isothermal experiment, Figure 11, was used for accurate measurement of pressure loss over a wider flow range than could be sustained in the combustion study and at better accuracy. It also enabled scalar dispersion measurements to be made across monolith elements using conserved scalar mapping. The pressure loss determines the thermodynamic cycle penalty for the combustor and information on the piece-to-piece uniformity of porous media elements. The scalar dispersion may be used to assess the effectiveness of the matrix element as a mixer, since the transfer of gas, and thus heat, normal to the bulk flow direction has a significant effect on the burner exit gas temperature profile.

The experiments were run from the shop air supply, as depicted in Figure 11. Pressure loss measurements were made with either a Betz secondary standard manometer or, for higher flows, calibrated pressure transducers.
Helium was used as a tracer gas to label the flow for the scalar transport measurements, aspirated to a VG PRIMA 600 mass spectrometer as the detection device. The performance of the mass spectrometer was checked against helium calibration standards. The x-y-z traversable probe for tracer

sampling was positioned to an accuracy of +/- 0.1mm and the traverse was conducted under automatic PC control. Data was acquired to PC and processed on-line, as before. The injector and sample tubes were both 1.1mm internal diameter (2mm o.d.) to represent point source and sample extraction. The injection and sample extraction were 3mm from the inlet and exit faces of the monolith to minimise wake spreading effects. The tube Reynolds Number (based on o.d.) was less than 2000 at all operating conditions. The monoliths were cut to different lengths to examine flow development effects. Alignment of the matrix relative to the flow tube/traverser reference was maintained to isolate structural effects on dispersion. Tracer injection was isokinetic, referred to the mass-mean velocity in the empty tube.



P1: 10bar transducer
P2: 3.5bar transducer
P3: 70mbar and 350mbar transducer
dP: 70mbar and 700mbar transducers + 40mbar Betz water manometer
T1,T2: K-type thermocouple

Figure 11a Arrangement for Pressure Loss

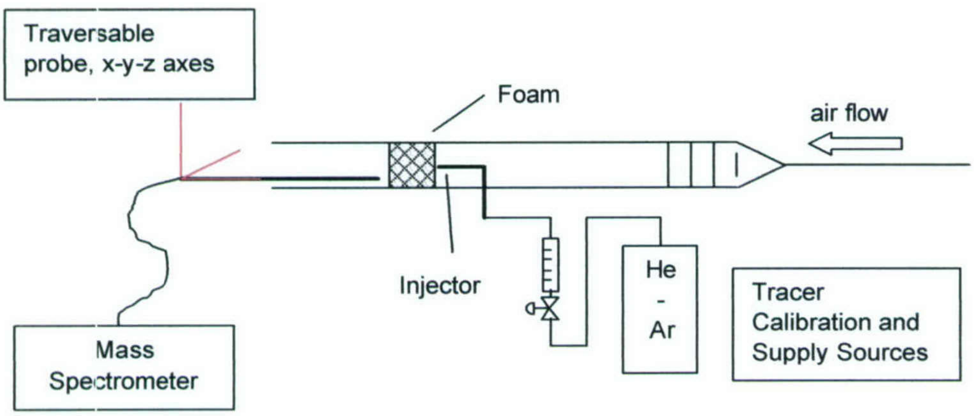


Figure 11b Additions for Scalar Transport

Figure 11 Schematic Arrangements for Pressure Loss and Scalar Dispersion

Results & Discussion

Several sets of matrix elements were used in the study, all of YZA material. The maximum operation of any one set was about 40hours, encompassing around 10 – 30 start/stops, in addition to the variations imposed during the experiment itself. Little damage to the ceramic was observed, although there was some alteration to its surface appearance in service: after this was noticed, element assemblies were aged in the rig prior to collecting full data sets. There has been no attempt to elucidate any contribution to combustion performance this surface change might have caused: no observable change in results was apparent and the effect is discounted in the analysis.

Much of the data reported was obtained in quasi steady-state, i.e. from slowly varied settings of the operational parameters for the rig over the course of an experimental trials point or campaign. It is presented mostly as time-traces of the measurements, post-processed where appropriate to allow for time alignment of the data and incorporation of calibration and scaling factors for pressure and gas analysis results. A selection of data is illustrated. Operation was generally at pressures of 1, 3, 5, 9 & 11-12 atmospheres, with inlet mixture temperatures to ~450K; operation at higher pressures and temperatures proved difficult due to increasing temperatures in the inlet (fine) matrix, leading to concern over flashback. Equivalence ratio (ER) has been used, defined as local fuel:air ratio divided by stoichiometric f.a.r.

Ignition Studies

All propulsion devices need simple, reliable, ignition performance. The majority of work reported in the literature for this class of combustion device employs ignition stabilized at the exit face of the matrix stack, as a surface-supported flame, which then back-propagates heat into the coarse pore element, ultimately permitting the flame to stabilize within the foam. This process, whilst suitable for generic laboratory work, is not appropriate for a practical device or operation in the high-pressure experiment, partly because of the time delay to bring the flame to its desired stability region and partly for safety and handling. Also, it was desired to *initiate* combustion at the interface between the fine and coarse pore matrices as part of the study.

Initially, the ignition method used an electrically heated fine-wire element embedded in the coarse pore matrix, local to the fine/coarse element interface. It was found that although this functioned, it was not sufficiently durable to serve reliably for the high pressure experiments. Ceramic sheathed elements were also tried but did not supply sufficient energy for consistent light-off performance; however simple sheathed element glowplugs provided a better solution. Standard small diesel engine units have been used, rated at about 36W. These are larger in size than would be desired for small combustor. Ignition both at the interface and at the matrix exit plane has been used, with the preferred method being at the interface. The glow plug is energised by a 12 volt lead acid battery. The ignition sequence is generally maintained for approximately two minutes while the fuel air mixture strength is restricted below ~0.8 ER to control the maximum temperature in the ceramic. Once ignition has been established in the allowable ER range, the glow plug is de-energised and the mixture strength is brought to the test value and combustion in the matrix is allowed to stabilise. The light-off duration reflects test rig operational and experiment needs. Two single fuels, methane and hydrogen were studied, together with their mixtures. The fuels were chosen to represent low and high flame speed substances.

Ignition Characteristics with Methane

Ignition performance for the two-matrix (fine + coarse) arrangement is similar over a range of inlet velocities. Figure 12 shows temperature data from the embedded thermocouples in the matrix assembly for a range of conditions and equivalence ratios. The legend refers to thermocouple position in the foam assembly: the digits give the downstream distance from the matrix inlet face in millimeters, the letter refers to thermocouple type. The ignition 'on' point (in time) is shown by the red vertical arrows on the horizontal axis and the 'off' point by blue arrows. Consistent ignition results are obtained at equivalence ratios ~0.4 – 0.5 over a velocity range from 0.3 – 0.9m/s. The final thermocouple located at 98.2mm from the exit face of the matrix is used to assess the presence of gas-phase reactions in the zone downstream of the coarse matrix. The intention throughout the experimental programme was to confine reactions to the porous assembly only.

The range of flow velocity shows that the Porous Matrix Combustor will accept thermal load increases without performance aberrations and is an indication of the relative load acceptance and controllability of the device when integrated in an engine. The flow velocity range is approximately one to eight times the laminar flame speed for methane at atmospheric pressure and equivalence ratios below 0.7.

Ignition and general combustion performance on other, multi-component, higher hydrocarbon fuels would be expected to be at least as good as that shown in Figure 12, since the Spontaneous Ignition Temperature for complex hydrocarbons tends to be much lower than for methane, e.g.CH_4 540C; C_3H_8 450C; AVTUR (Jet A) 255C [1].

To compare ignition performance with a more conventional geometry, the ignition characteristics of the glowplug PMB arrangement have been compared to other, private, data for a conventional liquid-fired (Jet A) gas turbine flame tube with a typical 12J surface discharge ignition system and aerodynamic flame stabilization. The results at atmospheric pressure are shown in Figure 13. To bring the data to a direct comparison, the total airflow for the aerodynamically stabilized reference combustor has been factored to account for a notional primary zone airflow split, which has then been reduced to a flow per unit cross-sectional area before comparison with the total airflow and mixture strength through the porous matrix unit. The comparison is satisfactory, with a flat response from the porous matrix combustor, at mixture conditions that would be within the range of experience for conventional GT systems and fuels.

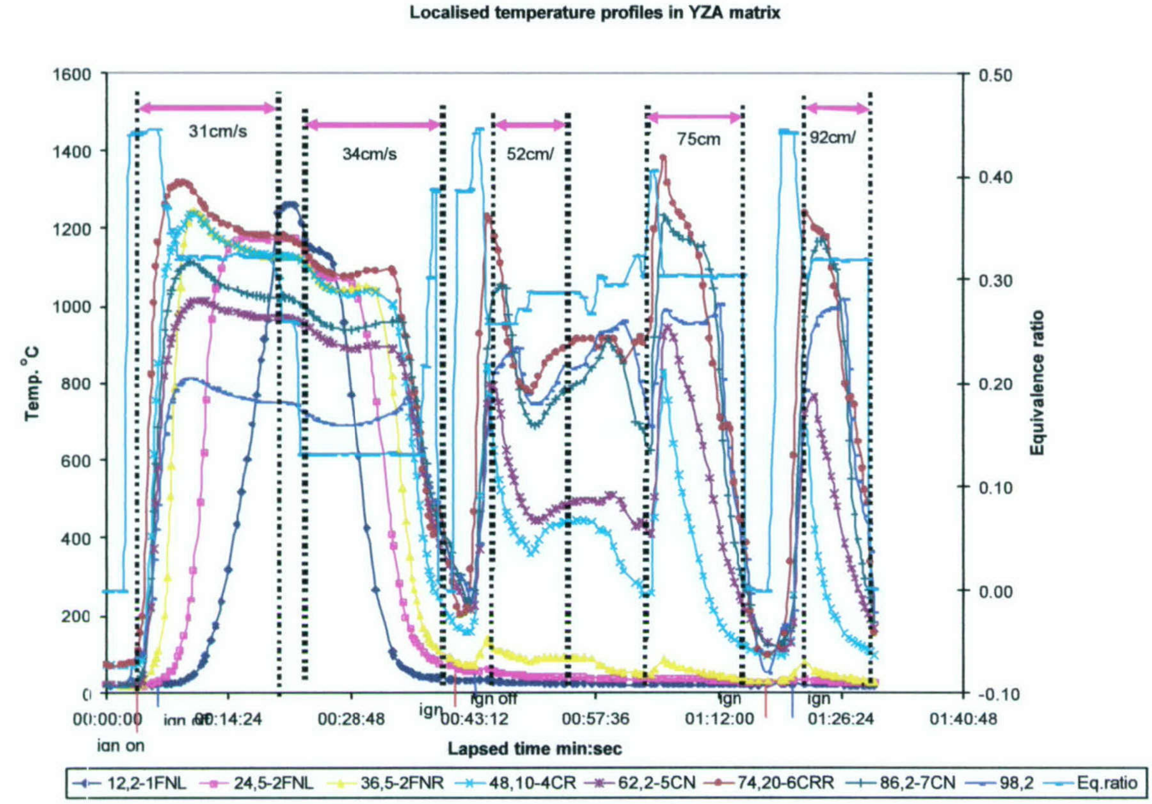


Figure 12 Typical Ignition Characteristics for a Range of Inlet Velocities and Equivalence Ratios, on Methane.

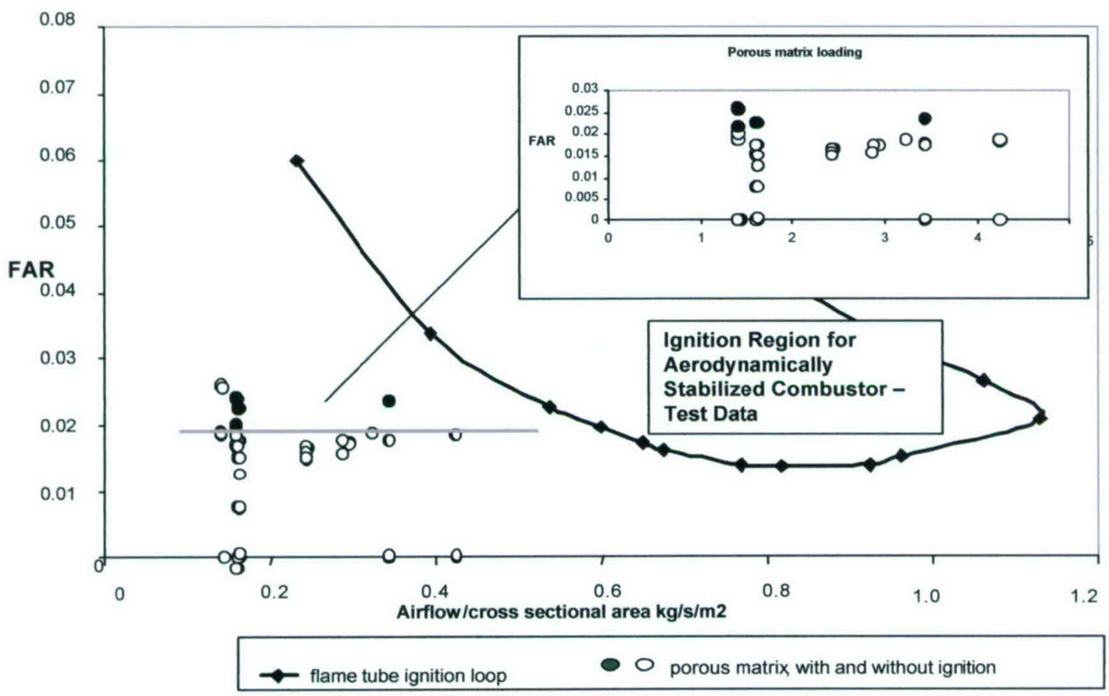


Figure 13 Loading Comparison between Aerodynamically-stabilized Flame Tube and Porous Matrix Burner.

Ignition with Methane-Hydrogen Mixtures and Hydrogen

For the methane and hydrogen mixture burnt in the 3-matrix assembly, the ignition sequence adopted was similar to the procedure described earlier but using the diesel glowplug at the interface between the two coarse matrices. The ignition sequence lasts approximately 2 minutes, with a fuel:air mixture strength of 0.75 equivalence ratio maintained. Once ignition has been established, the glow plug is de-energised, the mixture strength brought to lower values and combustion in the matrix allowed to stabilize. It was found necessary to first establish ignition with methane only as fuel and after gas temperature stability was observed in the exit gas stream, hydrogen could be added incrementally. Figure 14 shows the large exotherm obtained from addition of hydrogen. This involved careful operation to preserve the integrity of matrices. Figure 15 shows the exit gas temperature and the temperature inside the matrix local to the fine/coarse pore junction. Ignition here was initiated at ~ 300 kPa, equivalence ratio of 0.73, and a linear velocity of ~0.2 m/s. Combustion occurred in the fine pore material, showing the tendency of the higher flame speed fuel to propagate combustion upstream. This is not considered to be a limitation of the method, rather to show that careful control and choice of ignition method is necessary for high flame speed fuels. Although hydrogen proved sensitive to the ignition process – perhaps counter-intuitively, given its lower ignition energy (~0.02 c.f 0.28mJ for methane at room conditions [1]) – this appears to be due to the ignition system used. It is observed elsewhere that a hydrogen flame may not necessarily propagate easily transverse to the general flow direction.

Further work was not pursued: the primary purpose of the study was to establish the steady-state combustion performance of the burner.

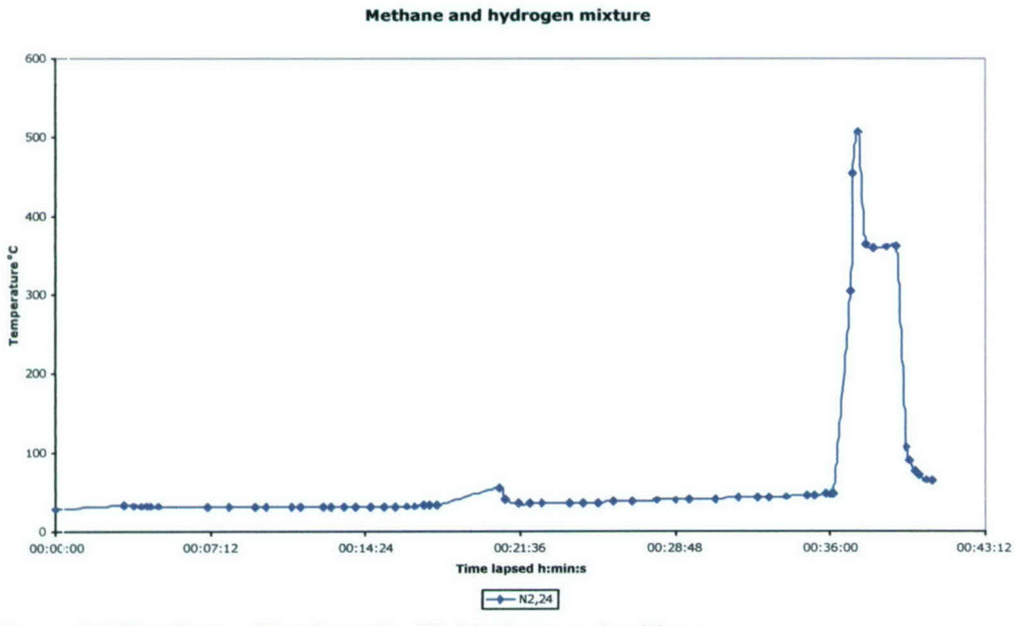


Figure 14 Exotherm Produced with Hydrogen Ignition.

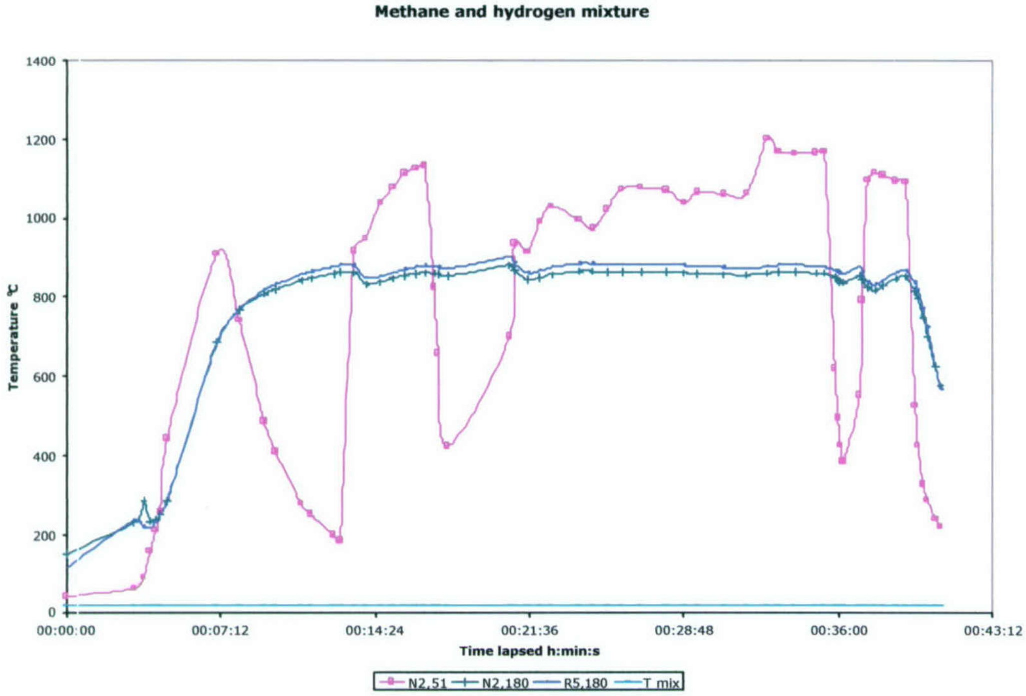


Figure 15 Exit Gas & 1 Matrix Temperature from Combustion of CH_4/H_2 Mixture in the 3-matrix Arrangement, showing large Excursions at the Fine/Coarse Pore Interface. Combined Hydrogen/Methane ER range 0.6 – 0.55.

Steady Combustion Characteristics

High Pressure Results with Methane

Consideration of the performance of free flames at elevated pressure suggests that the PMB concept would perform in similar fashion to a free flame, since the basic stabilization and ignition mechanism is similar in both cases. However, the split of energy recirculation mechanisms in the PMB is different from that in a flame. Energy transfer to fresh reactants has a higher fraction of radiant energy transmission (compared to a non-luminous flame) and so has a larger thermal input from the solid to the flow. The enhanced reactant temperature these mechanisms produce greatly offsets the reduced flame speed that occurs with pressure and equivalence ratio [2], leading to a wider stable bulk velocity range and burning range over which a PMB may operate compared to a free, flame. In addition to a wide operating range at lean equivalence ratios, which has benefits in emissions performance, the thermal re-distribution of energy accomplished in the ceramic matrix evens out the exit gas temperature profile.

Experiments have been conducted at a range of inlet conditions using as a template a high performance gas turbine cycle to set the parameters for the study, as given in Table 1.

Pressure, kPa	Mixture Inlet Temperature, K
1000	650
1500	710
2500	*805 } extended range*
3000	*830 } not covered here*

Table 1 Parameter Set for the High Pressure Experiments: modelled on a high performance gas turbine operating envelope and equivalence ratio range not exceeding 0.6: based on SL & 288K, isentropic compression and simple correction for compressor efficiency. Combustion confined to the porous elements of the combustor, equivalence ratio constrained to limit solid temperatures to 1600C.

The results show that a wide stable range can be obtained at much leaner mixtures than are possible in free flames, and that performance parameters such as gaseous emissions and exit temperature can be at least as good as conventional lean-burn turbulent flame combustors. The data will be described and discussed under several headings.

Operating Range – ambient inlet temperature

Figure 12 shows that the PMB will operate over a range of inlet velocity exceeding the laminar flame speed, S_L, by between a factor of 2 & 8 for reactants at ambient entry temperature and pressure. The quoted laminar burning velocity of methane at atmospheric conditions and ER=1 is ~0.43m/s [e.g. 1 etc]. Flame speed is severely reduced at low ER (S_L ~ 0.113m/s at ER = 0.6 & ambient temperature & pressure) and reduces with pressure, approximately as $(P)^{-n}$ where n ~0.5.

Data for methane at ER=0.6 can be expressed as

$S_L=0.113(P/P_0)^{(-0.61)}$ where P_0 is atmospheric pressure and P the operating pressure, at ambient inlet temperature [2].

Our experiments on the PMB at pressures to 1200kPa show that maximum velocities can be higher than 1m/s on CH_4, without reactant preheat. Using the relationship above gives an estimated laminar flame propagation velocity slightly less than 0.026m/s, i..e. operation about 40 times the laminar speed at the test condition. Figure 16 shows time-trace results for variable pressure operation to 1100kPa, inlet velocity 0.85m/s at room temperature, with maximum equivalence ratio 0.6. Here, the ER has been controlled to limit the solid material temperature of the matrices. The in-matrix temperatures are fairly consistent for the conditions covered and show good stability for the device. There is an appreciable temperature rise in the fine-pore matrix and the maximum temperature region occurs across the interface region at 1100kPa. It is likely that the flow velocity could be increased in this case whilst confining the reaction to the coarse pore element, but this has not been proved. The heat release is 6.7kW (net Heating Value basis) at the operating condition. Increasing the through velocity would raise the heat release in direct proportion.

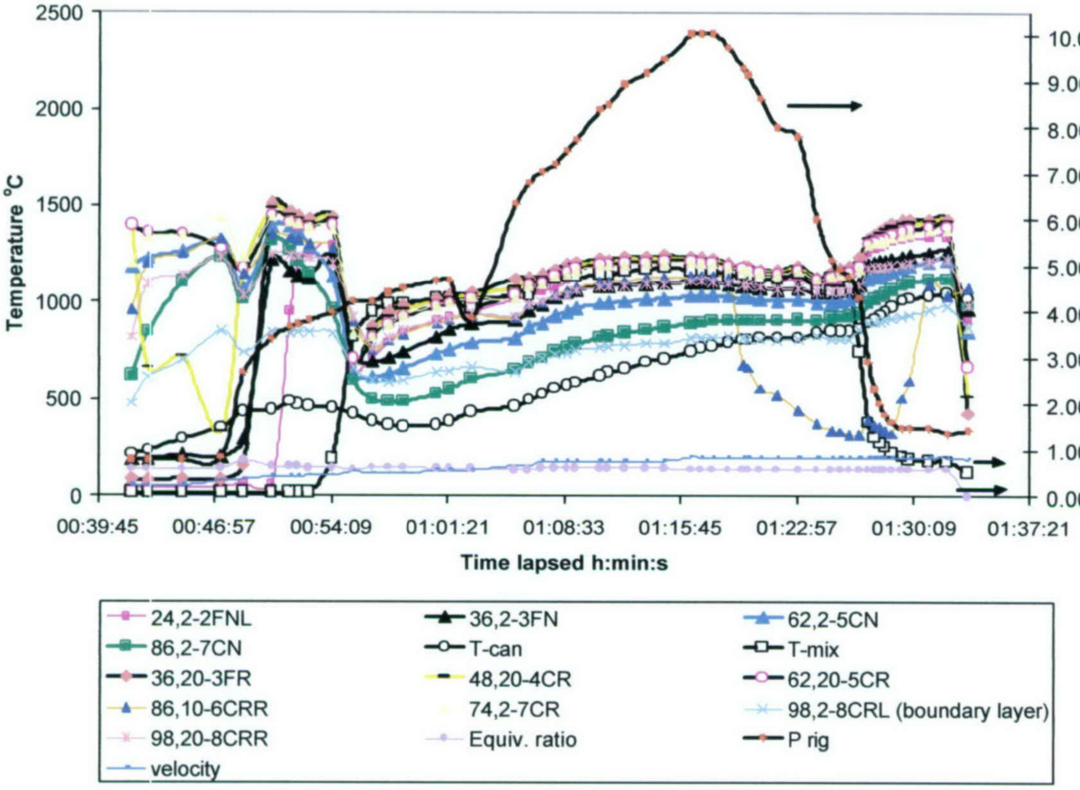


Figure 16 Operation at 1100kPa & Ambient Inlet Temperature on Methane: Legend as Figure 12.

The internal heat recirculation within the PMB can be assessed by comparing the calculated adiabatic equilibrium temperature at an operating point and the measured internal matrix temperatures. In this case, for an ER of 0.6, the adiabatic temperature is ~1680K, compared to a maximum measured value of 1504K at a pressure of 1003kPa, however the temperature distribution is quite flat along the matrix assembly. At lower pressures, ~150kPa, maximum temperatures of ~1600K were measured in the matrix assembly. Given the high, flat temperature distribution, considerable heat would have been lost to the surroundings by radiation from the end faces of the matrices at these conditions, so the measured temperatures are likely to be low. The claim of super-adiabatic temperature combustion may then be sustained. Figure 17 illustrates the axial temperature distribution: It suggests that to achieve optimum performance from this type of combustion system, control of the position of maximum heat release is necessary, making the two-pore-size device necessary for a practical embodiment.

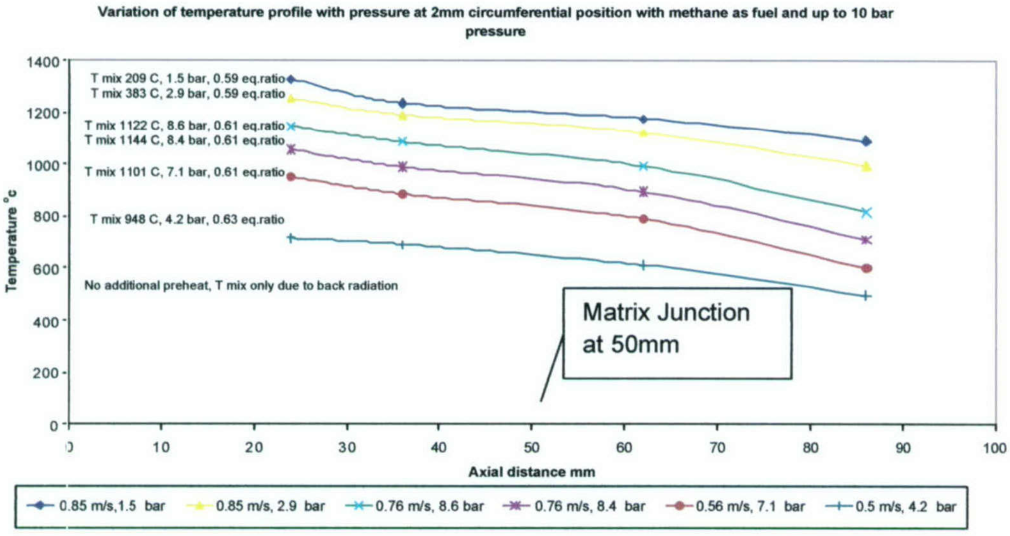


Figure 17 Matrix Temperature Distribution without Control of Flame Stabilization Position.

Operating Range – elevated inlet temperature

Similar trials were conducted with reactant preheat, and operated to confine the main reaction to the coarse matrix element. Typical results are shown in Figure 18.

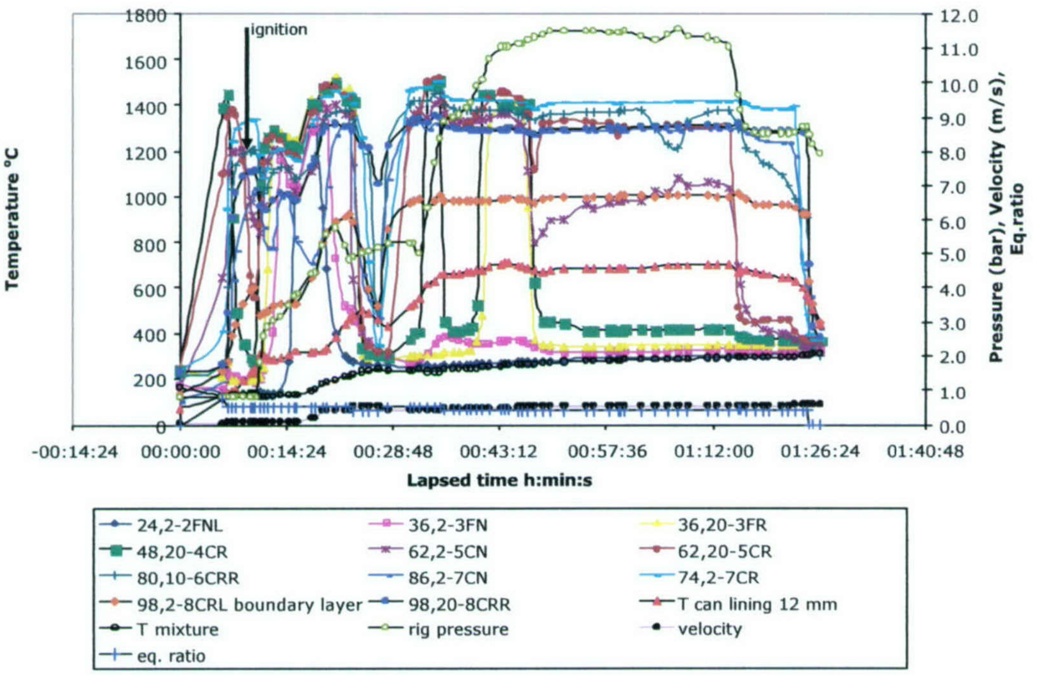


Figure 18 Performance at 1100kPa with Inlet Preheat. Legend as Figures 12 & 16.

The operational heat release rate at 1150kPa and preheat 544K is similar to the ambient temperature feed case (6.65kW), but with ER reduced to 0.43. Target maximum volumetric heat release rates for high-performance gas turbine combustors are of order 30-50 MW/atm.m^3 at full power (overall ER~0.4 – 0.6; preheat 750 – 850K). The corresponding value for the PMB is 2.95 for this trials point, i.e. 1/10th of target but with about half the preheat temperature and sustainable feed velocity. Increasing the ER, velocity and temperature to the maximum working temperature of the matrix materials would improve the loading in direct proportion – about 4 times the present value or ~40% of target, conservatively estimated.

The equilibrium temperature at this ER with allowance for preheat is ~1253K. The maximum measured matrix temperature is 1408C or 1781K, giving an apparent temperature enhancement due to super-adiabatic operation of ~500K. A principal benefit then is in specific fuel consumption, in direct ratio, however there remains an uncertainty over what the thermocouple measurement actually is: as noted earlier, it has been assumed to be solid temperature, but in the vicinity of maximum reaction this may be doubtful.

The axial temperature gradient, Figure 19, shows the elongated reaction zone at low velocity and high pressure (same data set). Apart from limiting the combustion loading of the device, operation at low velocity alters the energy balance in the upstream matrix and can allow combustion to occur in the fine pore upstream section, with consequent risk of flashback.

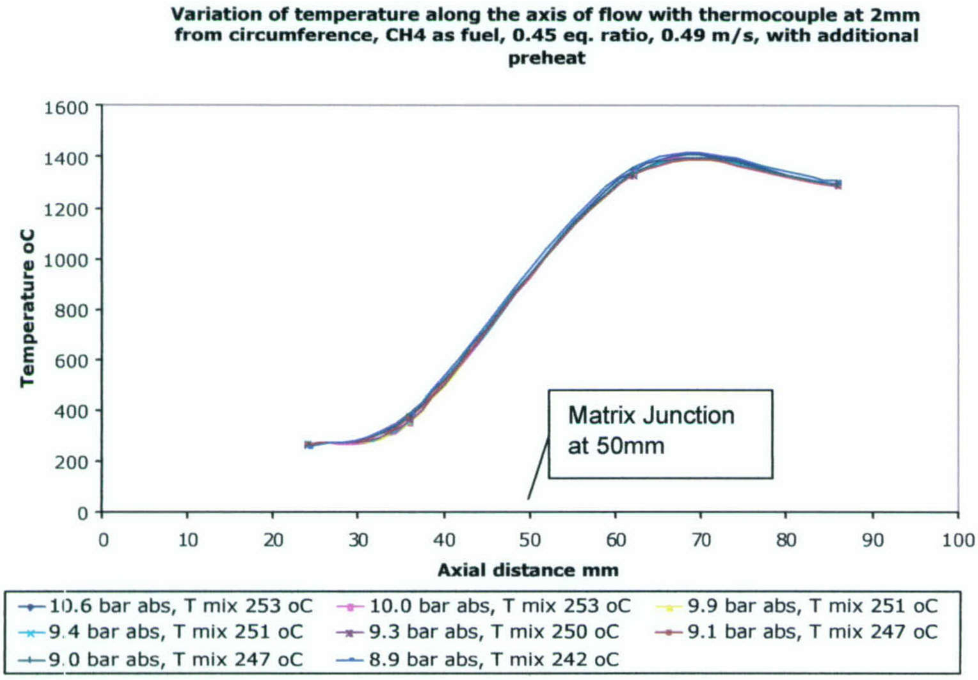


Figure 19 Axial Temperature Profile along the Combustor.

This behaviour is sensitive to pressure, as shown in Figure 20, covering pressures from 500 to 1100kPa at similar inlet temperatures.

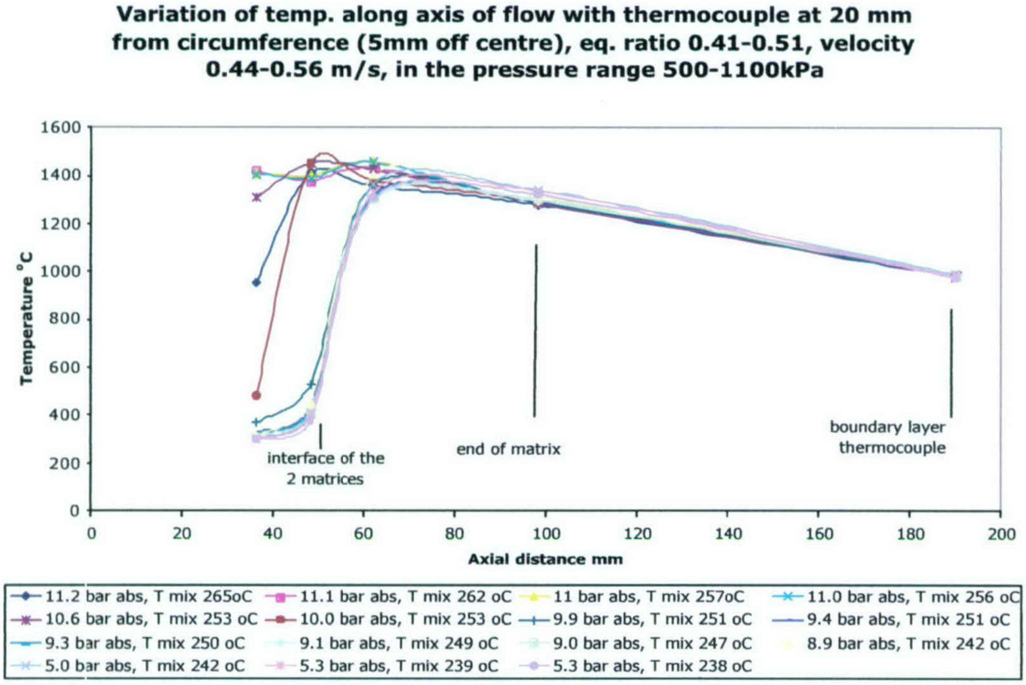


Figure 20 Alteration of Stable Operating Condition with Pressure.

A reduced data set, Figure 21, shows more clearly the narrow range of pressure associated with the change of location of peak temperature crossing the matrix fine/coarse junction.

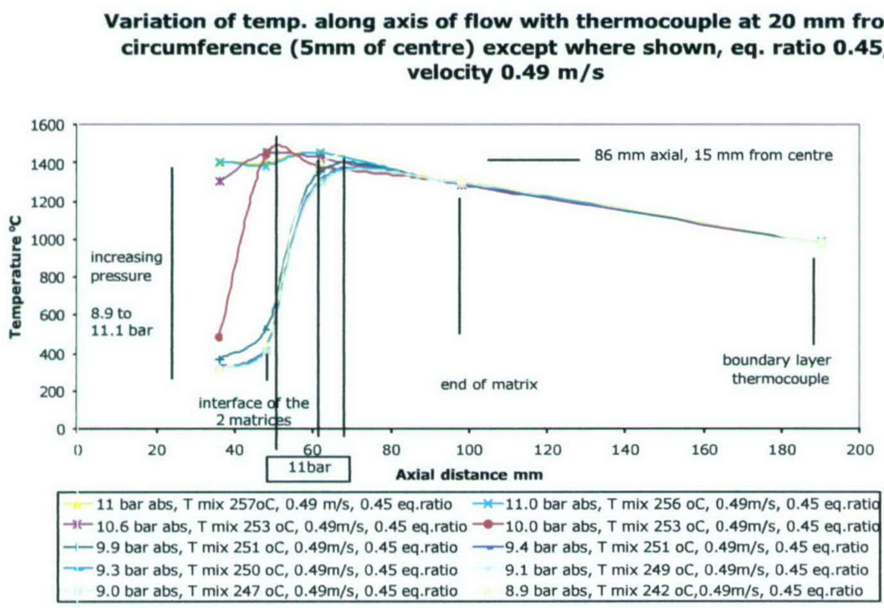


Figure 21 Reduced Data Set from Figure 20.

A criterion for flame propagation in porous media has been derived in terms of a critical Peclet Number (Pe) [3].

Propagation occurs for Pe ≥ 65, where

$$Pe = \frac{S_L d_{m.} c_{p.} \rho}{\lambda}$$

and:

S_L is the laminar flame velocity; d_m the equivalent porous cavity diameter; c_p the specific heat capacity, ρ the density and λ the heat conductivity of the gas mixture at inlet.

At the trial conditions, the largest influence is exerted by density, as the pore sizes, equivalence ratio and inlet temperature are essentially constant. There is a two-fold variation in pressure, with a 5% variation in temperature and an *estimated* 10% variation in flame speed, using classical theory and the relationship described earlier. Increases in density raise the operating pore Peclet Number for the matrix, allowing combustion to exist in smaller pores. The matrices are not perfectly uniform in pore size or distribution and this is may be an additional contribution to the variation in stabilization seen with density differences around 10 – 20%.

General Features

Combustion loading of a PMB is directly proportional to its operating equivalence ratio and feed velocity. The presence of enhanced reactant temperature due to heat recirculation, and the super-adiabatic operation thus achieved, means that design peak cycle temperatures can be achieved with lower equivalence ratios. This implies lower fuel consumption, proportional to the reduced ER, in a manner similar to the incorporation of a separate heat exchanger in the cycle, but without the complication and within a far smaller envelope. The maximum velocity in these experiments has been taken as that where all the reaction remains confined to the porous elements, as indicated by the gas temperature at the 98mm station and the final matrix temperature, i.e. the matrix temperature must be greater than the gas temperature. If combustion is allowed to continue in the gas downstream space, the overall loading rises proportionally.

As a comparative guide, it is unusual to find aerodynamically-stabilized lean-burn combustors operating at global ER much below ~0.55 – 0.6 due to lean extinction restrictions limiting the operability of the combustor. No data have been found to confirm the laminar flame speed relationship used here for ER below 0.6, but to obtain an indication of the benefit conferred on the combustion process by the heat recirculated in the matrix, an estimate may be made, assuming the form of the relationship given above to hold at leaner ER.

Liaison with the University of Texas

The companion study at UT was used to compare with and inform the choice of experiments at Cranfield. Calculations performed by Barra and Smucker during their project-sponsored Year 2 visit to Cranfield gave valuable insight. A joint paper [5] was produced by the two teams for presentation in 2003 at the ONR-instigated International Colloquium on Combustion & Noise Control. The computations agree broadly with the experimental data and give a higher maximum flow velocity than was reached in the experiments, whilst meeting the criterion of submerged combustion: this raises the combustion intensity.

Emissions

Experience at atmospheric pressure indicates very low emissions of the legislated pollutants, NO_x, CO and UHC from this type of device.

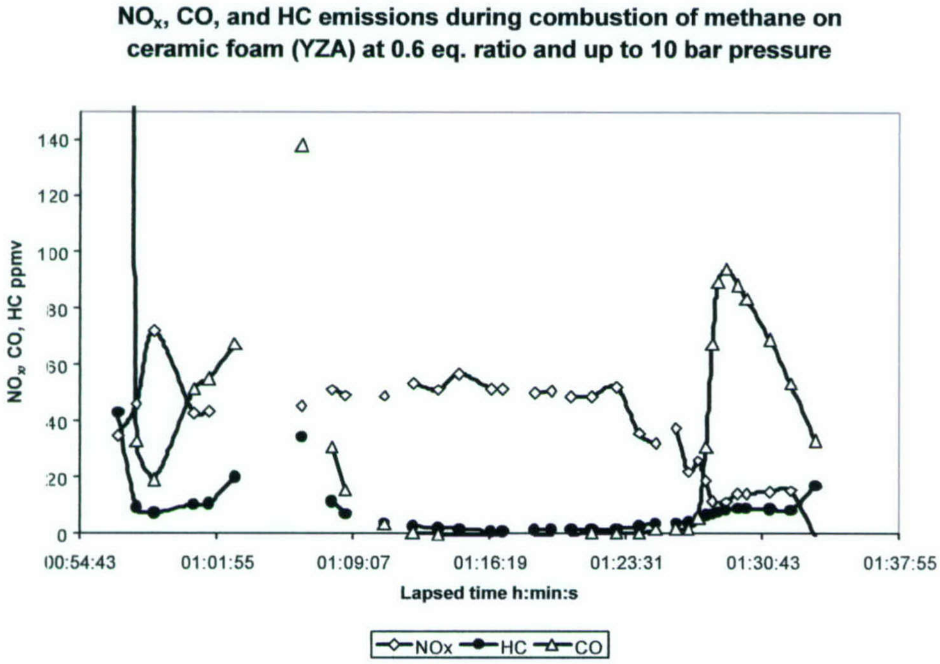


Figure 22 Emissions at Ambient Entry Temperature and 1000kPa; Conditions as Figure 17.

Figure 22 illustrates the measurements at 100kPa with ambient entry temperature. The very low levels of unburned hydrocarbon and carbon monoxide are noteworthy. The retention of high temperatures in the matrix contributes to their low levels, but there is substantial nitrogen oxide production, due to the high temperature existing across the entire matrix assembly. The excursions at the start and end of the record are associated with light-up and fuel system purge on shut-down.

Our experiments with preheated reactants at pressures to 1100kPa show these characteristics are preserved, as shown in Figure 23, which is a complete record from ignition to shut-down for a single trials point. The major difference in the combustion process here, compared to the preceding result, Figure 22, is control of the combustion zone position and size and ER (refer to Figure 21) giving very low values of CO and UHC, together with ultra-low NO_x. The negative values for NO_x indicate that the resolution of the analyzer was reached in this case. Analyser span and linearity were confirmed for a full-scale value of 25ppm for NO_x and 40ppm for CO. The residence time for the combustor is of order 120ms at the leanest equivalence ratio. The low levels of CO and UHC indicate high combustion efficiency, somewhat better than might be anticipated from an aerodynamically stabilized combustor operating at similar conditions of equivalence ratio. The NOx formation appears to be via the thermal, Zel'dovich, mechanism.

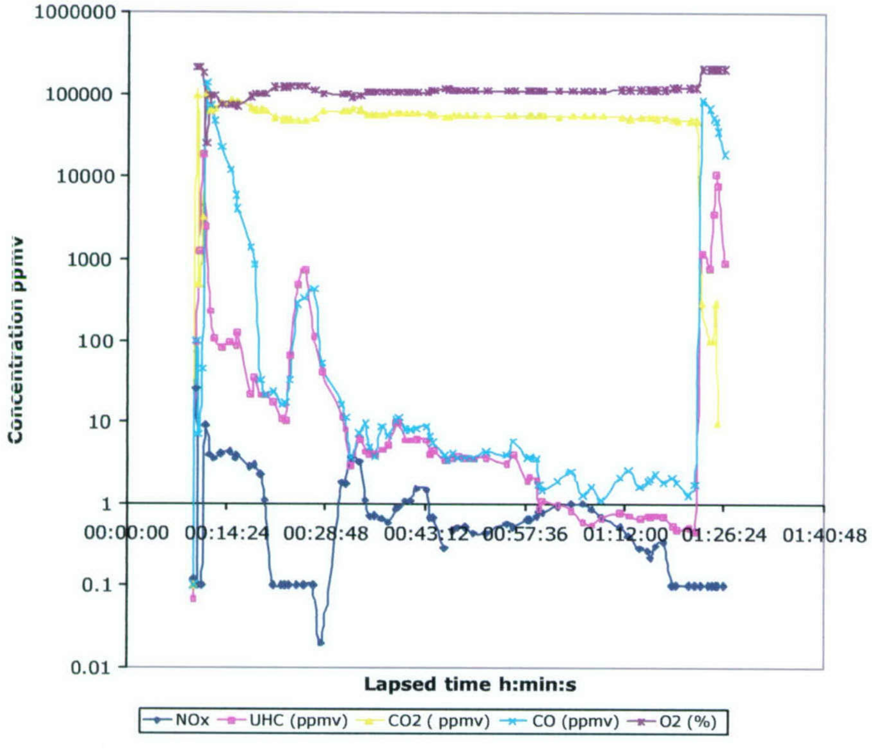


Figure 23 Single Trials Point Record for Gaseous Emissions, on CH_4 at 1100kPa and 450K Inlet Conditions as for Figure 18, ER=0.5.

Methane-Hydrogen Mixtures and Hydrogen

When including hydrogen in the reactants, in the 3-matrix unit, ignition was initiated first with methane and then hydrogen introduced to achieve the desired mixture. This procedure was adopted because the high burning velocity of hydrogen led to large temperature excursions. The ignition sequence was described earlier.

Figure 24 shows a complete single-point trial profile with mixed gas, covering a range of equivalence ratio from 0.6 to 0.5. With the addition of hydrogen, the combustion of the mixture is now spread across all three matrices. The higher flame speed of hydrogen is manifest here by the temperature in the fine matrix being higher than that of the coarse matrix, showing some of the fuel burns back against the flow direction. Combustion of mixed-gas does not proceed at the same rate for both constituents. If methane is added to the

PMB when operating on hydrogen alone, the exhaust gas composition indicates that all the methane is converted except for a peak amounting to ~1.5%CO that appears as it is added to the fuel, Figure 25.

The NO_x emissions stay below 10 ppm throughout but show an increasing trend as hydrogen is introduced incrementally, consistent with higher flame temperature.

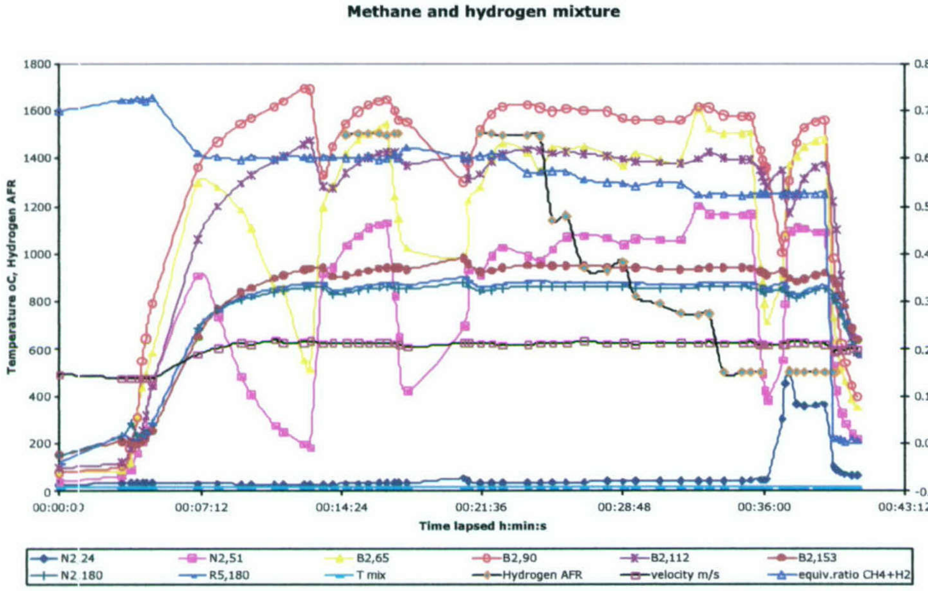


Figure 24 Temperature profiles of combustion of CH_4/H_2 mixture in the 3-matrix arrangement.

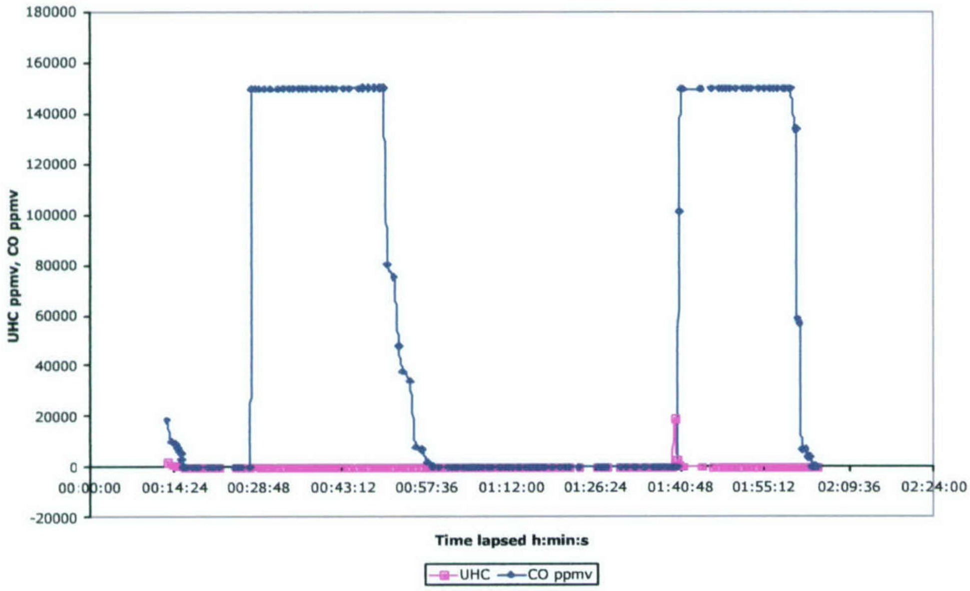


Figure 25 Effect of Adding Methane as a Step Change in Feed at Constant Hydrogen Flow, showing Incomplete Combustion of Methane.

Hydrogen alone can be burned in the PMB without risk of flashback. It is necessary to control the feed conditions more carefully than with methane. The dynamic response appears to be affected by the higher flame speed, as shown by the rapid variation in exit gas temperature, Figure 26. Fine feed rate control will contain the upstream propagation of the reaction.

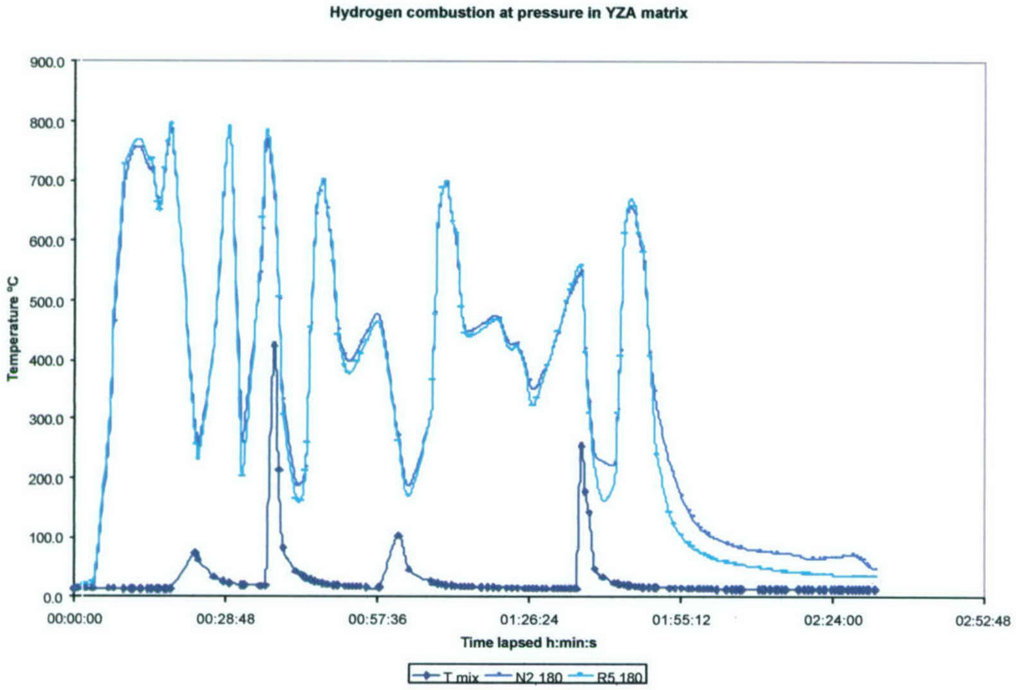


Figure 26 Exit Gas Temperature for H_2 Combustion at 300 kPa in the 3-matrix Arrangement.

Figures 27 and 28 show temperature profiles and product composition for stable hydrogen combustion at pressure of 3 kPa, linear velocity range of 0.2 – 0.3m/s and hydrogen equivalence ratio of ~0.22. The combustion of hydrogen is confined safely to a narrow band in the matrix assembly. At these operating conditions a substantial amount of hydrogen (7-8 % by volume) is slipping through unburned, as shown in Figure 12. This is consistent with the model of 'cellular' combustion zones advanced under the ignition section of the work, where considerable hydrogen slip was observed at the post-ignition condition.

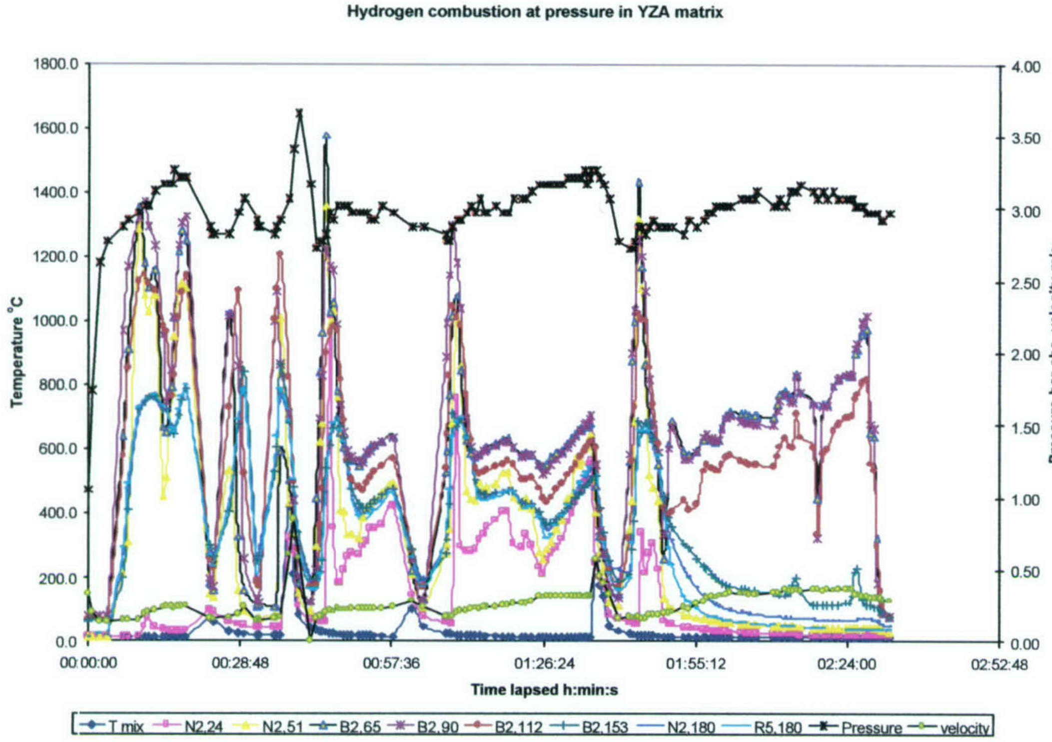


Figure 27 Temperature Profiles of Hydrogen Combustion at 300 kPa.

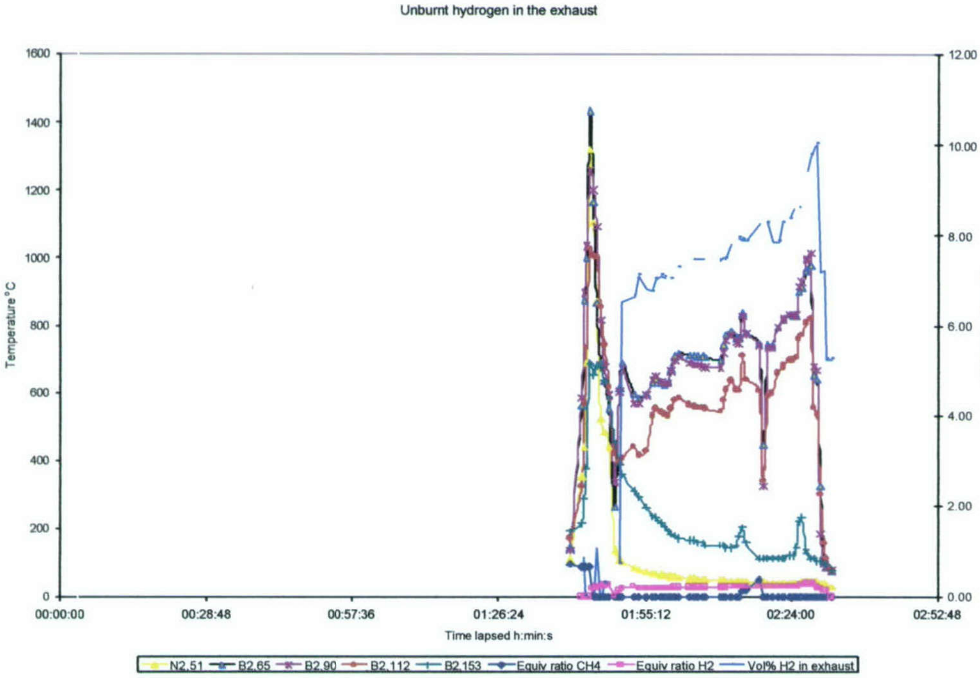


Figure 28 Unburned Hydrogen Remaining in the Exhaust at 300 kPa.

Weak Extinction and Temperature Traverse Quality or Pattern Factor

The weakest mixture at which combustor will burn is critical to its transient performance, load acceptance and rejection. Figure 29 shows in-matrix temperatures at atmospheric entry conditions with gradual reduction in equivalence ratio at constant velocity when operating with methane. This indicates a weak extinction limit of ~0.3 for well-mixed reactants. Simple experiments on the ignition rig have shown that equivalence ratios of ~0.25 can be sustained with a richer core flow on the matrix centreline.

The distribution of exit gas temperature depends on the inlet mixture spatial distribution. Diffusion of heat through the matrix by radiative, conductive and convective effects flattens the exit temperature profile, while radial heat loss can provide a cooler wall boundary layer region. To establish the order of radial heat losses, temperature measurements on the high pressure experiment, in the core of the matrix, adjacent to the outer radial wall and in the insulating mounting tube have been used to evaluate heat flux. The worst estimate of radial loss puts it at <4% of the total thermal input.

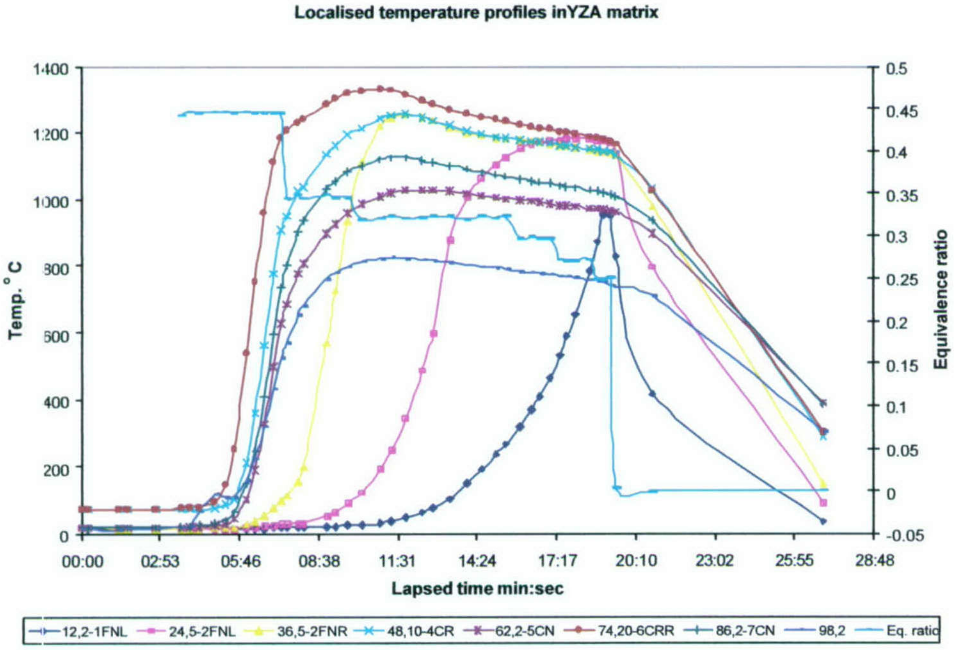


Figure 29 Weak Extinction, indicated by In-matrix Temperature Measurement.

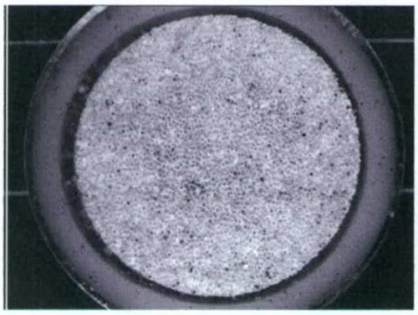
Pattern factor has little meaning in the context of the experiments, but the film-cooled exhaust tube provided complete integrity at the highest operational temperatures. Tailoring the exit temperature profile by cool air addition would require very little air, enabling most to be used in the combustion process; this solves one of the perennial combustor design problems, where there is frequently insufficient air to control combustion and provide adequate cooling.

Pressure Drop and Scalar Dispersion

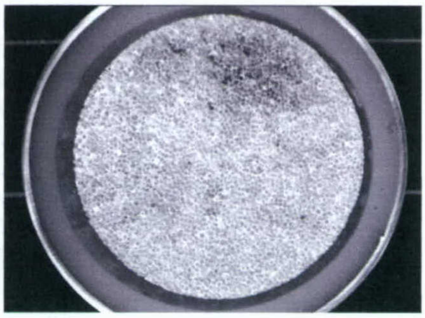
Some of the combustion results did not appear to fit the existing models of the process [3, 4] and it was evident from visual examination of the matrix pieces that there was pore blockage, uneven pore spatial distribution and pore size, especially in the coarse matrix pieces. The appearance of foam samples is shown in Figure 30, where the images have been generated by standard metallographic techniques of sectioning and polishing. To obtain information on the structures and their hydrodynamic pressure drop, image analysis and pressure loss measurements were performed.

The image analysis is at an early stage. The foams show appreciably different structures, with large geographical variations in open area, closed pores and pores partially obturated. The manufacturer's data gave porosity values of 70%. Porosity is defined as the pore space in the material, i.e. (1-(bulk density/material density)), as distinct from permeability, which is the material's resistance to flow.

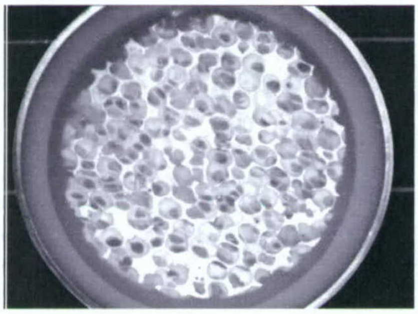
Measurements of the isothermal pressure loss of the porous elements of our combustor at ambient conditions over flow ranges from 0.001 to 0.06 Mach Number (approximately 0.3 to 20m/s at ambient conditions) showed a quadratic dependence of loss on velocity of the form $Ax^2 + Bx$. The linear term is related to the viscous or Darcy term, whilst the square-law dependence is due to the blockage and Bernoulli effects.



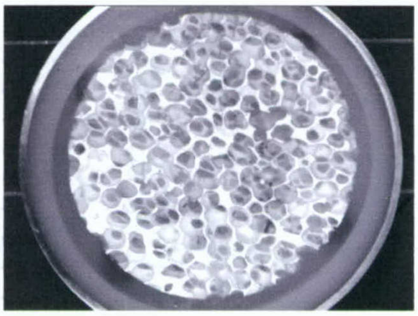
Fine: Sample B



Fine: sample D



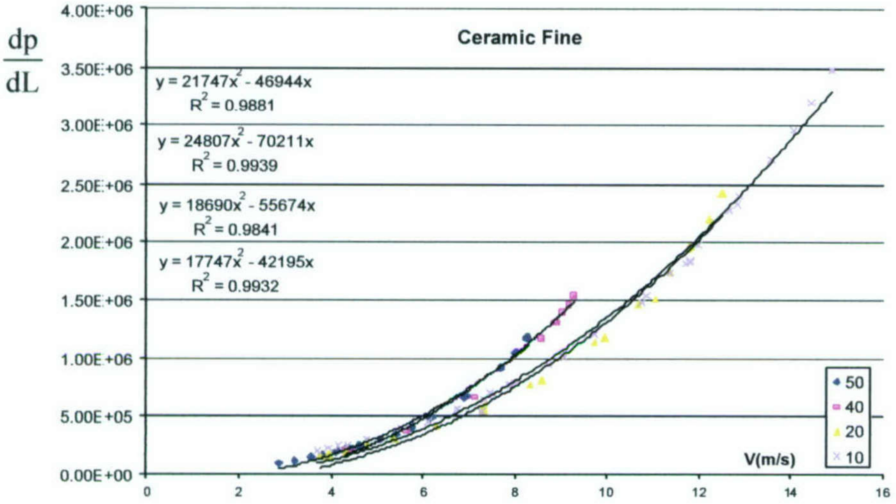
Coarse: Sample C

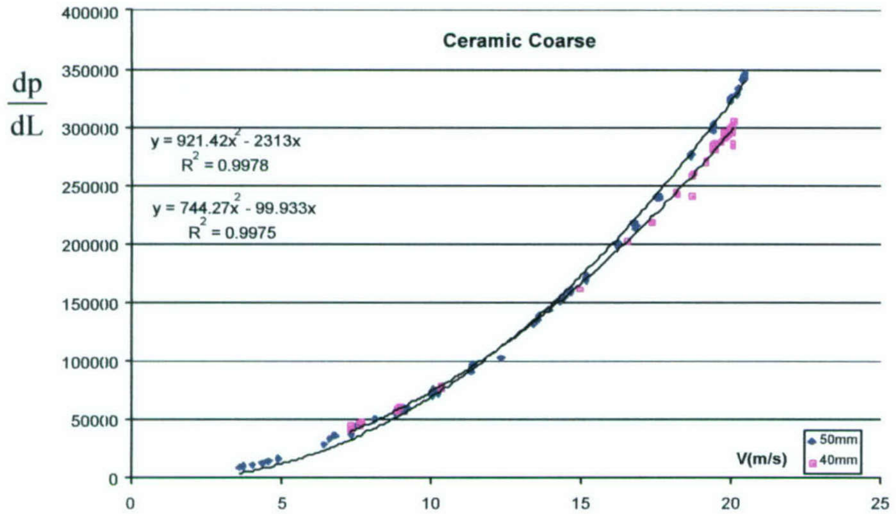


Coarse: Sample E

Figure 30 Sectioned Foam Elements.

The fine pore material exhibits a loss about one order larger than the coarse. For the fine and coarse 50mm elements, the pressure loss of each could be given by the expressions shown graphically in Figures 31 & 32. The length-dependence of pressure loss was established for lengths up to 50mm for individual elements: element losses may be superposed. Values are in kPa.





Figures 31 & 32 Isothermal Pressure Loss for the Foam Materials.

Radial dispersion measurements were undertaken using scalar tracer measurement to examine the convective mixing in the foam elements. The measurement of dispersion is useful in the mathematical modelling of the process, which was used to inform the experiments during the course of the study, as well as to give a physical understanding of the transport processes in the matrix assembly. Transverse dispersion only has been measured:

longitudinal dispersion is neglected as being small in the general (axial) flow direction. At the velocities of interest, the mechanical displacement of fluid packets is the primary mechanism of scalar transport.

Measurements were also taken with the tube empty and the same injection and sample stations to permit direct comparison with the natural, wake-spreading characteristic of the flow, thereby showing the role of the porous element as a mixer.

Some typical iso-concentration contours are shown in Figure 33 for two matrix types, fine and coarse pore in different lengths, sampled at the same downstream location and with dispersion through the same length of matrix in each case. The matrix element diameter is 50mm and the elements were cut to give the lengths shown. A qualitative measure of relative mixing is given by the area contained within the 50% concentration contour, which is shown to the same scale in each view and compared to the empty-tube jet-flow base case. The effect of different tracer injection rate was examined for the coarse material as some variability was observed during the experiments: this is illustrated at the longest element length. There are wide differences evident in mixing rate and structural topography, covering an order difference in mixedness compared to the jet-flow base case.

A three-dimensional representation of the evolving mixing in the fine matrix is illustrated in Figure 34, compiled from one, super-posed, data set.

The degree of structural non-uniformity in the foam can be discerned from the regularity of its tracer map. Figure 35 shows a typical result for the fine ceramic material, with abrupt changes of structure that even out with length. All plots approximate to Gaussian distributions.

The porosity in both coarse and fine foams is nominally 70%. Comparison with a pre-existing relationship [6] relating the dispersion coefficient to the porosity conforms well to these results.

$$\frac{D_R}{D_m} = 1 + \frac{63}{320}\sqrt{2(1-\varepsilon)}P_{ed}$$

Where D_R and D_m are the radial and longitudinal dispersion, respectively; P_{ed} is the dispersion Peclet Number and ε the porosity. The equation is sensitive to the value of porosity: it was not possible to make independent measurements of this and the supplier's data was used in the calculation.
The experimental values are compared are in Table 2 below

	Dr mean	Dr eqn
CF Helium	3.3E-04	2.67E-04
CC Helium	8E-04	8.30E-04

Table 2 Comparison of Measured & Calculated Dispersion Coefficients.

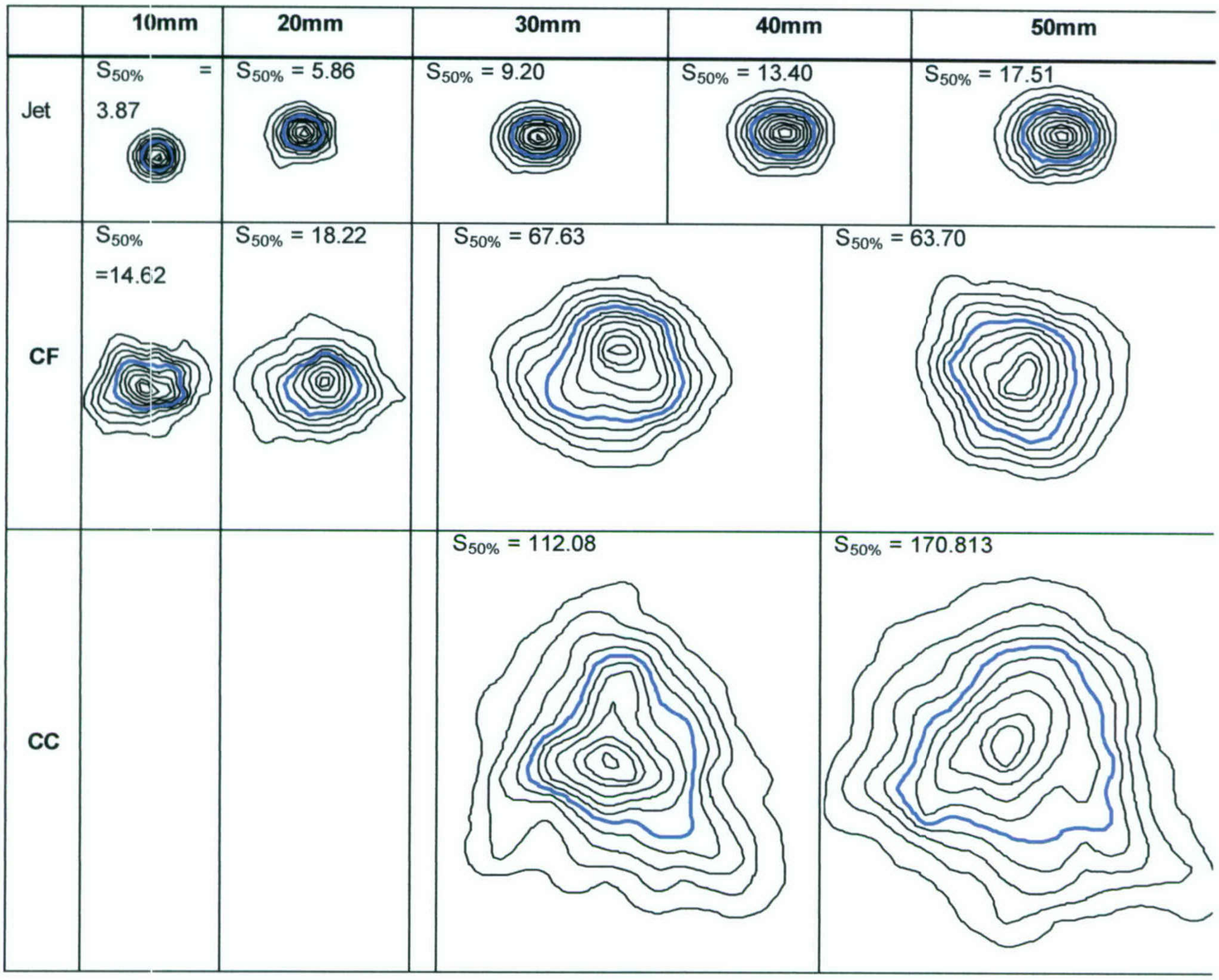


Figure 33 Scalar Maps at Different Axial Stations for Fine & Coarse Pore Elements.

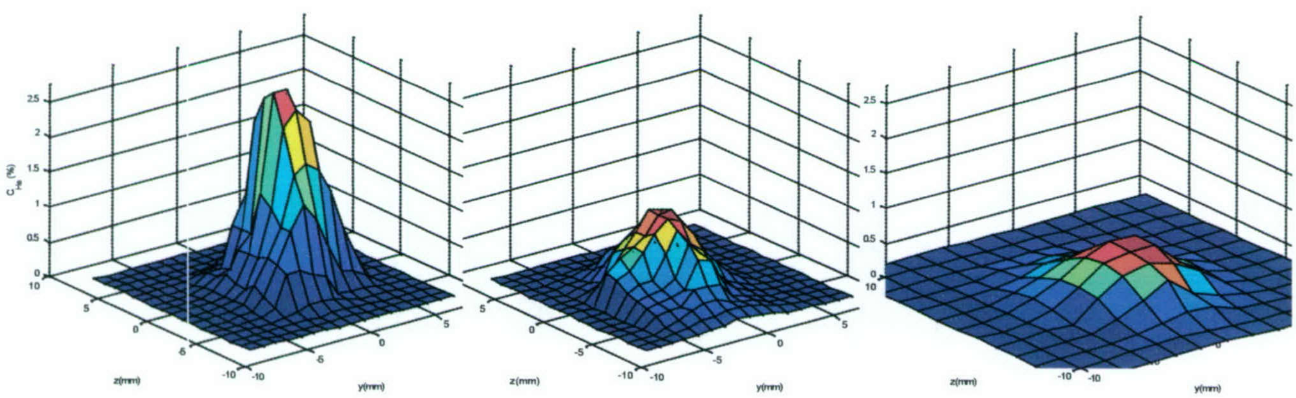


Figure 34 Scalar Field Development in Fine Ceramic Material at 10, 20 and 40mm Lengths

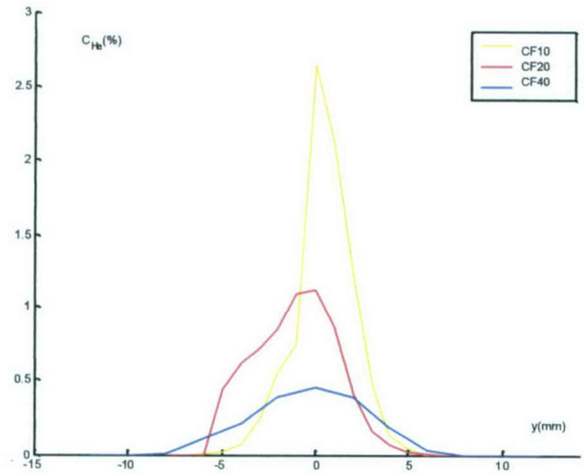


Figure 35 Planar Cross-section Concentration Profiles (same plane) for the data of Figure 34.

The foams are effective mixing devices, especially the coarse pore example, with a ten-fold increase in the 50% concentration contour area compared to the free-jet case at the longest element length. The effect is most pronounced for lengths above 40mm or about 20pore diameters. Large webs between pores can be seen in Figure 30 and it appears these have a role in this case, compared to the result for the fine-pore material. The fine-pore matrix is also an effective mixer and together the matrices play a significant part in the fuel preparation for the combustor and temperature uniformity within the PMB and in its exit flow. Figure 36 shows solid structure-dependent temperature effects.

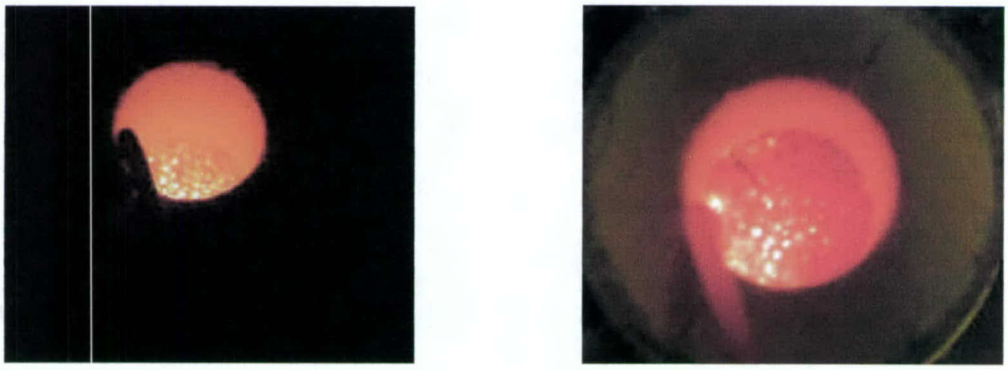


Figure 36 Visible Images of the PMB, showing Structure Effects, left at High ER (~0.4) and right at low ER (~0.25).

In terms of penalty to thermodynamic propulsion cycles, the PMB pressure losses are not greatly different from other, aerodynamically stabilized, combustors and do not appear to pose a limitation of application.

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Conclusions

A preliminary assessment of a model combustor in which the reaction is stabilized in a porous medium (PMB) has been made by studying its performance at elevated pressures and inlet temperatures. The burner has two close-coupled sections of reticulated ceramic foam of different pore sizes in which the combustion is established at the section interface and continues in the downstream, coarse pore section. The reason for using two pore sizes is to stabilize the ignition location and inhibit flame propagation in the upstream, fine-pore section, making the process safer and more flexible.

Combustion loading, emissions and stability have been determined over a wide range of conditions. The combustion characteristics of any type of porous matrix combustor have not been studied extensively at elevated pressures hitherto. Fuels used have been methane, methane/hydrogen mixtures and hydrogen. The ignition process and method has been briefly examined with reference to a practical combustor. The model combustor used was cylindrical and constructed to be quasi-adiabatic, permitting results to be extrapolated on the frontal area of the unit.

The study has the following primary conclusions

- Super-adiabatic combustion, referred to the inlet conditions is obtained: the degree of temperature enhancement can be large and offers a method of reducing specific fuel consumption in an engine cycle by internally using heat within the combustor to enhance feed reaction rate and temperature.

- The super-adiabatic regime enables stable, pulsation-free combustion at much weaker fuel:air ratios than in conventional aerodynamically-stabilized combustors. A range of fuels, considered by flame speed, can be burned in the device, without modification. This offers some scope for highly reactive fuels.

- Super-adiabatic operation offsets the deleterious effects of high pressure operation with lean mixtures on flame speed: efficient combustion is possible at flow speeds in excess of four to six times the laminar flame speed for given inlet reaction conditions. Volumetric heat release rates to about 40% of the study target value lower limit (target range ~30-50 MW/atm.m^3) appear practical with an optimized system.

- The emissions characteristics are consistent with predictions for the operating equivalence ratio for all the fuels and conditions examined. Low values of NO_x CO and UHC were obtained, at least as good as for conventional units.

- Durability of the matrices was good: no damage was found within operating durations of ~40hours per matrix assembly.

- Simple ignition systems based on hot-tip glowplugs provide a usable ignition method for bench work but more attention is required to produce a rapid-response system for a practical combustor.

- The transport properties of the foams used mean that comparatively simple fuel preparation and injection processes can be used. The intrinsic pressure losses are low, however, and within the range associated with conventional combustion systems. It is known that liquid fuels may also be used.

- At present, the maximum operating temperature and therefore combustion loading, is set by the service temperature of the matrix material. Simple, zirconia-based ceramics only were available for these experiments, limited to about 1600C but complex composites or alumina-based materials offer another 200 – 300C potential. This would considerably enhance heat release rates, reducing combustor volume.

- There is no cooling requirement for the combustor: this means simplification in its design and more freedom in using the engine's air.

The PMB's properties of stable, high temperature operation at lean equivalence ratios, low emissions, and relative freedom in geometric design offer attractions for gas turbines and other propulsion engines, especially those where conventional turbulent flame designs may involve small sizes and unconventional shapes.

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14. ABSTRACT

A preliminary assessment has been made of a combustor in which the reaction is stabilized in a porous, incombustible medium. Its performance at elevated pressures and inlet temperatures has been studied, with emissions and stability determined over a wide range of conditions, together with the pressure loss and diffusivity of the porous matrix elements from which the combustor is made. The combustor was formed of reticulated porous ceramics, untreated to augment or sustain chemical reaction. The characteristics of combustion within porous media which are attractive in a propulsion context are the ability to burn leaner and hotter than a free flame, with low emissions, no cooling requirement for the combustor itself and the potential to operate free from combustion-induced noise. The reduced combustion loading resulting from lean burn operation is partially offset by heat transferred within the porous matrix raising the maximum reaction temperature. Data has been obtained at pressures to 1200kPa, reactant preheat to 700K, with methane, methane-hydrogen mixtures and hydrogen alone. The results show that the combustor operates in a "super-adiabatic" mode, with low emissions. Intrinsic pressure loss is within values commonly accepted for propulsion gas turbines. No durability problems were found, within operating durations of ~40hours per matrix assembly.

15. SUBJECT TERMS

COMBUSTION; POROUS MEDIA; PROPULSION; EMISSIONS; FUELS; GAS TURBINES

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