THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Three Park Avenue, New York, N.Y. 10016-5990

99-GT-116

INVESTIGATION OF IGNITION PROBABILITY IN A GAS TURBINE COMBUSTOR USING LASER IGNITION.

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ABSTRACT
For an aircraft gas turbine engine, the ignition performance is usually expressed in terms of the range of flight conditions over which stable combustion can be established. At present, the size of an aircraft's gas turbine combustor is governed predominately by its altitude relight performance and is principally derived from existing empirical design rules. These indicate the volume required to give adequate primary zone airodynamic loading to achieve the desired relight performance. A possible means of improving altitude relight performance is to relocate the point of ignition away from the combustor wall to a more favourable location within the combustion chamber. One way of achieving this is through the use of laser ignition. Reported in the paper is an initial programme of work in which the possibility of using laser ignition has been investigated in a gas turbine research combustor operating at several inlet conditions. Comparative results show that, when sited at the same location, laser ignition gave no noticeable improvement in ignition performance when compared to a standard surface discharge igniter (SDI). However, by using laser ignition to locate the ignition site away from the combustor wall, the range of combustor mass flow and AFR at which ≥75% ignition probability could be achieved was increased by approximately 33%.

In conjunction with the experimental study, an ignition probability model, based on the local magnitude of a Karlovitz stretch factor, has been developed to identify suitable regions within the combustor in which to apply laser ignition. The Karlovitz parameter gives an indication as to whether or not a flame kernel will propagate successfully and has been used in conjunction with flow field and scalar distributions generated by Computational Fluid Dynamics (CFD) to yield a 2D map of ignition probability. However, the sensitivity shown by the model to the accuracy of the CFD predictions meant that reliable estimates of optimum ignition sites could only be obtained using experimental fuel and turbulence intensity distributions.

INTRODUCTION
For an aircraft gas turbine engine, the ignition performance is usually expressed in terms of the range of flight conditions over which stable combustion can be established. However, in-flight flameout may result from a variety of circumstances. For example, transient changes in engine airflow during manoeuvres exhaust gas ingestion following the release of ordnance, and severe ingestion of ice, water or dust can all terminate combustion. Whatever the cause, an engine relight will be required. The combustor environment under high

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Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Indianapolis, Indiana — June 7–June 10, 1999

altitude (i.e. 10000 m) relight conditions is extremely arduous and as a result, the aircraft may have to descend to lower altitudes for relight; whether the mission is military or civil, this is undesirable.

The size of an aircraft gas turbine combustor is predominately governed by its altitude relight performance. At present, the necesary combustor size for relight capability is typically determined using empirical design rules. These indicate the volume required for adequate primary zone air flow loading (or residence time) to achieve the desired relight performance. However, if relight capability could be improved, combustion chambers could be made much more compact, with direct weight and cost reduction benefits. Much larger weight saving would be associated with resultant shorter shafts, connecting turbines and compressors, and smaller engine casings. Furthermore, reduction in combustor size would also yield performance benefits, particularly with regards to NOx emissions.

A number of strategies have been proposed to enhance relight capability, including the use of oxygen enrichment [1, 2], novel fuel ignitors [3] and altering the location of, and the amount of energy deposited by, the igniter within the combustor [4, 5]. The study of Wilson and co-workers [4] indicated that improvements in ignition performance were attainable if the igniter was moved to more favourable (in terms of local aerodynamic flow field and mixture strength) locations within the combustors primary zone. However, potentially much greater improvements may be achievable if the ignition site could be relocated away from the wall of the combustor altogether. Such a move would not only ensure that ignition is sited in the most favourable location, but also negate any influence that the combustor wall itself may have on the ignition process. For example, during the early stages of a flame kernel's development, it is possible that the relatively small kernel could propagate, or be bodily convected into, the wall of the combustion chamber due to the random nature of the local turbulent flow field. Such an occurrence could result in partial, or complete quench of the kernel.

One way of achieving 'remote' ignition is through the use of laser ignition. The possibility of using a focused laser beam to ignite a combustible mixture has been recognised for a number of years [6, 7]. Its principal advantage over conventional ignition is the ability to site ignition at the most favourable region within the combustor. Additionally, the laser system potentially offers more repeatable energy deposition into the reactants and can overcome excessive energy loss to the ignition circuit, which typically can be of the order of 70% of the unit energy [8, 9]. Another potential benefit of laser ignition is that it could be developed so that multiple site ignition, distributed throughout the combustor volume, could be used. This may significantly reduce the time required to reach a stable combustion regime, with obvious benefits in terms of improving performance during the period of engine acceleration following successful ignition.

To assess the feasibility of utilising laser ignition in a gas turbine combustor, a preliminary programme of work has been carried out using laser ignition to ignite a research gas turbine combustor over a range of inlet operating conditions. The results of this study are reported here.

Although laser ignition provides a means of achieving remote ignition, designs rules are also required to identify optimum locations within a combustor at which to site the ignition. Currently available empirical design rules for acceptable altitude relight capability give no insight into the mechanisms involved, or the role played by the igniter and its location. They only indicate conditions that have, in general, previously proved successful under broadly similar temperature, pressure and fluidic regimes. Consequently, they are unable to indicate optimum ignition sites within a combustor. As an alternative to this empirical approach, Wilson and co-workers [4] implemented a method based on a parameter called the Karlovitz Stretch Factor, K. This parameter, which gives an indication as to whether or not a flame will propagate, was used in conjunction with a computational fluid dynamic (CFD) flow and scalar field prediction. This resulted in a two dimensional map of probability of flame propagation being generated. Based on this map, Wilson et al. [4] were able to identify a number of sites that offered better ignition performance as a result of enhanced initial flame kernel propagation. This approach has been adopted in the current work to identify suitable sites for laser ignition.

EXPERIMENTAL APPARATUS

The experimental investigation employed a 77° sector of an annular combustor containing three 'T' shaped vaporisers, equi-spaced at an angle of 27.7°, Figure 1. This configuration was chosen so that the outboard sections shielded the central section of the sector from flow distortions due to sidewall effects. The combustor geometry included both inner and outer primary holes circumferentially positioned in line with the vaporisers, whilst inner and outer dilution ports were located (circumferentially) both on the vaporiser centre line and between vaporisers. The air casing and combustor end walls were manufactured from Perspex to allow optical access to the combustor cavity. A full description of the combustor is available elsewhere [10]. The air velocity and fuel distributions within the combustor had previously been determined using gas sampling, pitot probe and LDA techniques [10, 11].

A uniform airflow was delivered to the combustor via a 600 mm diameter by 1 m long plenum chamber, located immediately upstream of the combustor inlet. Air was supplied to the plenum by a Keith Blackman five-stage compressor at a maximum mass flow rate of 1.59 kg/s at absolute inlet pressure and temperature of approximately 1.06 bar and 326 K, respectively. The combustor was fuelled using propane (95% minimum purity) which was regulated to an absolute pressure of 6 bar. Clearly, under conditions of altitude relight it is unlikely that the fuel would be fully vapourised and thus, the use of a gaseous fuel such as propane to represent this situation would be unrealistic. However, for the purposes of this study, where the relative improvements in performance between different ignition sites and systems is considered, as well as for experimental convenience, the use of propane is justified. Furthermore, to assess the feasibility of using the Karlovitz stretch factor to predict reliable ignition sites within a combustor, burning velocity data is required for the fuel in question. At present, there is a dearth of available information on the burning velocities of kerosene fuel sprays at conditions considered here (i.e. atmospheric pressure and 326 K). In contrast, the burning velocity of propane is available.

The amount of fuel delivered to the vaporiser was controlled by a Fisher Controls 1100 rotameter and a solenoid valve arrangement. The role of the solenoid valve was to limit the duration of the combustion event by supplying fuel for a fixed period of only 4 seconds following ignition to prevent damage to the Perspex side walls. A 4 second burn period was adequate to determine whether or not successful ignition had occurred. The operation of the solenoid valve and the firing of the ignition source, either laser or conventional surface discharge, was controlled by a manually operated ignition unit. To allow time for the fuel flow through the vaporiser to attain steady state prior to ignition, the solenoid valve was automatically opened 5 seconds before discharging the ignition system. Following the combustion event, there was a 1 minute delay before the ignition unit could be re-armed, thus ensuring that the combustor was completely flushed of all previous combustion products.

To generate the laser induced ignition breakdown, the second harmonic output (532 nm) of a 'Q'-switched Nd:YAG laser was used. A single 10 ns pulse of laser light was focussed, via 200 mm bi-convex lens, into the internal cavity of the combustor at the desired location, Figure 2. To reduce the size of the focus beam volume, and hence increase the local energy density, the laser beam was expanded from its initial diameter of 6 mm to a diameter of 24 mm via a x4 telescope prior to focusing.

An estimate of the amount of energy absorbed by air during the laser ignition breakdown was obtained by measuring the energy entering and exiting the ignition site using a pyroelectric (OPHIR PE50BB/DIF) power meter positioned either immediately before or after the laser focus point, depending on which parameter was being measured. The difference between these two measurements, obtained over a number of laser ignitions (typically 100), gave an estimate of the energy typically absorbed by the air during breakdown. For ease of optical access, this investigation was carried out in a fanned stirred combustion vessel, using the same optical arrangement used in the gas turbine experiments. The 350 mm diameter stainless steel combustion vessel was equiped with four fans symmetrically disposed in a regular tetrahedron configuration. The fans were used to induce varying degrees of turbulence within the vessel. Three pairs of orthogonal 150 mm diameter windows provided optical access. The investigations were conducted for a range of turbulence levels at a pressure of 1 bar and 358 K; it was found that the measured levels of energy absorbed during breakdown were independent of the turbulence level.

Shown in Figure 3 is the energy absorbed during breakdown plotted against that delivered. Above a delivered energy of 100 mJ, figure 3 suggests that the rate of absorption increases approximately linearly with energy delivered, at a gradient of about 0.6; although the actual data would suggest that, over the range of energies considered, there was a slight increase in the amount of energy absorbed with increasing energy delivered, Table 1. However, for the work reported here a linear relationship was assumed. The laser was operated at an output energy level of 315 mJ; following losses due to optics, this resulted in a delivered breakdown energy of 176 mJ. Of this, according to Figure 3, about 110 mJ was absorbed by the gas during breakdown.

In addition to the laser ignition system, ignition studies were also carried out in the gas turbine sector using a conventional surface discharge ignition system. This utilised a purpose built ignition unit that delivered a 12 Joule pulse to a standard Smiths Industries surface discharge igniter (SDI). This resulted in up to 3 Joule being available at the spark. The SDI ignitor was located downstream of the central vaporiser, on a plane that passed through the vaporiser inlet, as indicated in Figure 4. In reality, an aero-engine of the type shown in Figure 1 would probably used a igniter/primer combination to ensure reliable low pressure and temperature start-up. The exclusion of the primer in the programme of work does not effect the comparison between conventional and laser ignition systems.

PREDICTION OF IGNITION PROBABILITY.

The ideal way to model the ignition process would be via a comprehensive model that accounted for the liberation of spark energy and the subsequent processes governing the propagation of the flame kernel towards successful combustion. However, such a scheme would currently be at best, unwieldy and difficult to use as a flexible design tool. Therefore, other alternatives have been proposed based on empirical methods in which a 'characteristic time' for evaporation and mixing are used to model ignition [13]. However, a failing of this type of approach is that the location of the ignitor and the local characteristics affecting the developing flame kernel, both fluidic and chemical, is not considered.

One parameter that accounts for the fluidic and chemical influences affecting a growing flame kernel is the Karlovitz stretch factor, K. This parameter, which gives an indication as to whether or not a flame will propagate at a given location within a reactive flow, has been used on previous occasions to predict ignition performance [4, 14] by inferring a probability of successful flame kernel propagation following spark breakdown. When K is combined with a 3-D Computational Fluid Dynamic (CFD) flow and scalar field prediction, the influence of igniter location can also, to some extent, be accounted for [4]. Following Rizk and Mongia [15], the inclusion of a converged CFD solution also enables predicted values of such parameters as rms turbulent velocity, local equivalence ratio, length scales, etc. to be made without resorting to assumptions. Such parameters are not only interesting in themselves but also required in the evaluation of K.

To calculate the Karlovitz stretch factor, K, a computer programme known as KARL was invoked [4]. This programme interrogates the output of a converged CFD solution to extract standard solution data and then calculate, along with several associated parameters, the value of K, given by

$$K = \frac{u'}{\lambda}\frac{\delta_\ell}{u_\ell} \qquad (1)$$

where u' is the rms turbulent velocity, λ is Taylor macro scale of turbulence, δ_ℓ is the laminar flame thickness and u_ℓ is laminar burning velocity. The ratio u'/λ can be regarded as a measure of the aerodynamic rate of strain, or eddy life time, and δ_ℓ/u_ℓ a measure of the chemical life time, or reciprocal chemical strain rate. The laminar flame thickness can be obtained from $\delta_\ell = \nu/u_\ell$ [16], where ν is the kinematic viscosity. Assuming the flow field within each computational cell to be isotropic, the variable u' can be obtained from the CFD predicted turbulent kinetic energy, KE, by [17]:

$$u' = \left(\frac{2}{3}KE\right)^{0.5} \qquad (2)$$

The Taylor macro length scale was derived using [17]:

$$\frac{\lambda^2}{L} = \frac{A}{u'} \qquad (3)$$

Where A is a constant assigned a value of 40.4 by Abdel-Gayed and Bradley [18]. The integral length scale, L, was calculated from

$$L = \frac{C_d\, KE^{3/2}}{\varepsilon} \qquad (4)$$

Where ε is the turbulent energy dissipation rate, obtained from CFD, and Cd is a constant assigned a value of 0.202 [18]. Invoking the turbulent Reynolds number, R_T (= u'L/v), and substituting for λ and δ_ℓ into Equation 1, gives:

$$K = 0.157\left(\frac{u'}{u_\ell}\right)^2 R_T^{-0.5} \qquad (5)$$

Using Equation 5, the local value of Karlovitz number, K, was calculated for each point the computation solution domain and used to infer a probability of successful ignition

For the work reported here, the Rolls-Royce suite of computer codes known as PACE (Prediction and Analysis of Combustion Emissions) were used for the CFD calculations. The main computer code in PACE is based on a variant of that described by Jones and Priddin [19] and Jones et al. [20]. The version of the code used for the work reported here solved equations for the finite difference representations of mass continuity, scalar conservation, momentum, turbulence energy generation and dissipation. To accommodate the fluctuating turbulent velocity components, the finite difference formulations include a k-ε turbulence sub-model, after Launder and Spalding [21].

The research combustor used in the experimental programme utilised fuel injectors of the vaporiser type. To construct a CFD solution for this type of combustor, mirrored symmetry boundary conditions were employed. The physical shape of the vaporiser was then defined by 'blocking out' those mesh nodes associated with the region of space occupied by the vaporiser. This blocked region, which had a castellated rather than a smooth surface, was assigned the same properties as a solid wall. The fuel was considered to be evenly distributed on the blocked out surface representing the vaporiser exit, resulting in a uniform profile of fuel fraction entering the solution domain.

In the CFD model of the research combustor, conditions were assumed to be isothermal. This assumption is valid as the flow field in the actual combustor would be non-reacting prior to ignition. A 13.85° sector was simulated, this being the smallest repeatable circumferential section of a full annular version of the combustor. The computational grid had 90 mesh nodes in the axial direction, 41 in the radial direction and 22 in the circumferential direction, Figure 5, and extended from the centreline of the vaporiser inlet to a plane midway between vaporiser outlets. The inlet temperature and pressure adopted in the experimental test programme, along with the air and fuel mass flow rates were used to define overall combustor inlet boundary conditions. An empirical 1-D airflow analysis program [22] was used to predict the proportion of total mass, and mean flow injection angles, through each of the various air inlet features. The inlet boundary conditions for turbulent energy were calculated using a turbulence intensity of 5% of the mean velocity through each feature; the dissipation rate was calculated using a length scale based on a characteristic length for each feature.

The PACE model uses chemical equilibrium to calculate the local species concentration, and hence the local density at a point within the grid. Consequently, because the model was operated in an isothermal mode, the usual density-fuel fraction relationship included within PACE was not valid for ignition probability studies. Therefore, a relationship between fuel fraction and mixture density was derived from the equation of state and the respective relative molecular masses.

RESULTS AND DISCUSSION

A consequence of adopting laser igniton is a reduction in the duration of the ignition event compared to that of a surface discharge igniter (SDI) system; 10 ns compared to 100 μs typically for the SDI. It is known [23] that a significant reduction in spark duration can lead to an increase in the minimum energy required to ignite a mixture. This is associated with an increase in radiative or conductive heat loss, and/or the formation of a stronger shock wave at shorter spark durations. Since the laser ignition system delivered only a fraction of the energy delivered by the SDI system (110 mJ compared to approximately 3 J, based on an assumed energy loss of 70%), it was of interest to see whether or not the laser approach was capable of matching the SDI ignition performance when igniting the mixture at the same location. Initially, it was proposed that both methods would be used to ignite the mixture at the conventional SDI wall mounted position, downstream from the central vaporiser, Figure 4. However, on attempting to ignite the mixture with the laser at this location, it was observed that breakdown occurred on the combustor wall and not at the laser focus point. To circumvent this, the laser breakdown was therefore moved to a site 6 mm directly below the SDI location; any closer and the breakdown would revert back to the combustor wall.

Plotted in Figure 6 are data for greater than ≥75% successful ignition probability, for both the SDI and laser ignition at close to the conventional wall mounted location. With the exception of the lowest mass flow rate of 0.07 kg/s, both methods appear to produce very similar trends in ignition performance with increasing combustor mass flow at this location. This would suggest that the likelihood of successful ignition is a function of environmental factors, such as the local air fuel ratio and the local aerodynamic flow field, rather than the mode of ignition (i.e. laser or SDI). A similar conclusion was reached by Ronney [6], who suggested that the ignition energy requirements were not substantially different between a conventional and laser ignition systems.

The principal benefit of laser ignition would therefore seem to be its ability to locate the ignition source away from the combustor wall. Shown in Figure 7 is a two dimensional contour plot of the Karlovitz number, K, on a plane passing through the vaporiser inlet calculated for a sector mass flow rate of 0.21 kgs^{-1} at inlet pressure and temperature of 1.06 bar (abs) and 326 K, respectively. The combustor air fuel ratio was set to 40:1. The value of K at each point on the contour map was derived via the CFD solution using Equation 5, as outlined in the preceding section. The local value of K can be used to assess whether or not a newly ignited flame kernel located at a particular point in the combustor will develop successfully into stable combustion. Based on earlier work, Bradley et al. [14] identified three different regimes of flame propagation in a turbulent environment. With increasing flame stretch, as quantified by an increase in the value of K, the structure of the flame moves from being one of a continuous flame sheet into a regime of partial quench, in which the flame structure becomes highly fragmented. At sufficiently high values of K, the flame will be quenched completely. These regimes were also found to have a dependency on Lewis number, Le. More recently, Bradley et al. [24] showed that the onset of flame quench was associated with a value of the product of K and Le of about 1.5. Wilson [25] assumed Le had a value of unity and thus, the most suitable site for the growth of a flame kernel following ignition would be one that had a value of K somewhat lower than 1.5. In Figure 7, regions of K ≥ 1.5 are coloured black.

The distribution of K in Figure 7 suggests that the most beneficial location for successful ignition is in the head of the combustor, between the vaporiser and the combustor's outer wall. Two ignition sites remote to the combustor wall, Figures 8 & 9, were therefore located in this region to assess the potential of laser ignition to enhance ignition performance. Shown in Figure 10 is the range of air fuel ratios (AFR's) and mass flow rates at which a minimum ignition probability of ≥75% was obtained for the two remote laser ignition sites (Figures 8 & 9). Also plotted is the corresponding performance of the conventional SDI. For Site 1, little gain in ignition capability when compared to SDI ignition was noted. The axial location of Site 1 is roughly similar to that of the SDI but, radially, it is positioned approximately half way between the vaporiser and the outer combustor wall. In this part of the combustor, Figure 7 suggests the value of K is very similar at both the SDI location and laser ignition Site 1. Thus, a growing flame kernel at either location would experience similar fluidic and chemical influences; consequently, similar ignition performance is not surprising. However, the similarity of the results would also suggest that the presence of the combustor wall has had little or no influence on the SDI's ability to successfully ignite the mixture. Under certain conditions it is possible that the relatively small kernel could propagate, or be bodily convected, to the combustor wall and quench. However, because of the similarity of the SDI and laser ignition results, one would surmise that, following ignition, the small flame kernel was immediately convected away from the ignition site into the main cavity of the combustor before it underwent significant growth. Tilston [26] has shown that, following ignition, the small flame kernel can be convected over relatively large distances within a gas turbine combustor before it undergoes significant growth. In addition, Bradley and Critchley [27] proposed the presence of a force, generated electromagnetically during breakdown, that tends to propel the ignition kernel away from the surface of the SDI.

In contrast to the results for Site 1, laser ignition at Site 2 resulted in an approximately 33% increase in the range of combustor mass flows at which ≥75% ignition probability could be achieved when compared to the SDI, Figure 10. This was accompanied by a corresponding increase in AFR. Although there is scatter in the data, it could also be argued that for mass flows covered by SDI ignition (0.05 to 0.2 kg/s), laser ignition at Site 2 enabled the AFR at which ≥75% ignition probability could be achieved to be increased by approximately 25%. Both of these effects will result in a widening of the ignition loop for the combustor. This may then be reflected in a significant improvement in the relight capability of the engine.

The computed value of K at Site 2 is approximately 10% smaller than at the SDI location. This reduction is associated with a richer local AFR at Site 2 rather than a decrease in flow field turbulent intensity, as illustrated by Figures 11 & 12. Associated with the increase in air fuel ratio is a corresponding change in the laminar burning velocity of the propane-air mixture and, consequently, a change in the value of K (Equation 5). The relationship between the laminar burning velocity of a propane-air mixture and equivalence ratio (the actual fuel air ratio divided by the stoichiometric fuel air ratio) is given in Figure 13. It can be seen that the value of burning velocity peaks at an equivalence ratio of about 1.1. Richer or leaner than this, the burning velocity decreases. The smaller value of K predicted for Site 2 suggests that the growing flame kernel is able to develop more easily into stable combustion, than at either Site 1 or the conventional SDI position. At these locations the detrimental influence of turbulence in reducing the flame propagation rate is more dominant.

The distributions of K indicated by Figure 7 would suggest that laser ignition at Site 2 offers, potentially, the best improvement in ignition performance. To confirm this prediction, ignition probability was investigated via laser ignition at a wide range of sites within the combustor. Presented in Figure 14 are the resultant ignition probabilities at three radii at different axial locations within a plane which passes through the vaporiser inlet. Also indicated on this figure is the ignition probability associated with the SDI. The ratios indicate the number of successful ignitions to the number tried; a 8/8 ratio indicates a 100% success rate. These tests were carried out at the same inlet conditions used previously, i.e. mass flow rate of 0.21 kg/s for at an inlet pressure and temperature of 1.16 bar (abs) and 310 K, respectively; the combustor overall AFR was 40:1. The results of this investigation (Figure 14) shows a surprising degree of variability in ignition performance within the combustor. More pointedly, there appears to be a dramatic drop off between areas of good ignition performance and those of very poor performance; the possible reason for this difference is discussed later. However, comparison between the best laser ignition probability (near the inner combustor wall between the vaporiser and the primary port location, Figure 14) and that recorded for the SDI shows that, at the operating conditions considered, there is a 25% increase in ignition performance if the site of the ignition event is relocated away from the combustor wall. However, it should be noted that the location of the optimum ignition site may vary, with changing inlet conditions.

Clearly, the lean ignition limit in the research combustor can be improve through the use of laser ignition. However, other novel igniter concepts have also demonstrated an ability to enhance the lean ignition limit. The work of Low et al. [3, 4] suggested that, by adopting a Plasma Jet Igniter, the lean limit could be increased by about 16%. Whilst this is less than the improvement noted here for laser ignition, the Plasma Jet Igniter gain would currently be a cheaper and more practical methed of extending the lean ignition limit than laser ignition. However, with the advent of modern, low-cost solid-state diode lasers this situation may change. Furthermore, the potential availability of a relatively cheap laser source may allow laser ignition to be utilised at a number of sites simultaneously within the combustor. Such a move may lead to a significant improvement in ignition capability. Nevertheless, there are still a number of challenges (i.e. the effects of beam attenuation, optic fouling, thermal stability, reliability, etc.) to be addressed regarding the use of laser ignition in a gas turbine combustor and these may prove insurmountable, both in terms of practicality and cost.

Considering the data in Figure 7 and Figure 14, there is clearly a conflict. From Figure 7 one would infer (based on the value of K) that ignition performance in the lower half of the combustor would be generally very poor. Whereas the measured data in Figure 14 shows that the opposite is true. The values of K shown in Figure 7 were derived by using Equation 5 in conjunction with a CFD prediction of the aerodynamic flow field and fuel fraction distribution within the combustor, Figures 11 & 12. As discussed earlier, the distribution of calculated turbulent energy is relatively uniform throughout the combustor and has been confirmed, to some extent, by experimental data [11]. However, Figure 11 indicates that the CFD has predicted a large region of very rich mixture under and directly ahead of the vaporiser. This rich mixture strength means that the associated calculated laminar burning velocity, u_ℓ, will also be small (as u_ℓ decreases at rich AFRs, Figure 13), resulting in a high value of K. As part of another research programme, measurements were made of a scalar flux distribution within the research combustor [10], Figure 15. These measurements were obtained by sampling a ethylene trace gas introduced into the vaporiser flow to represent propane, and indicate that, on plane passing through the vaporiser inlet, the actual area associated with a high fuel fraction below the vaporiser is significantly smaller than that predicted by the CFD. In addition, the experimental data also highlights an area of high 'fuel' concentration above the vaporiser at the head of the combustor and only a moderate 'fuel' concentration directly in front of the vaporiser. Downstream of the outer primary port, for both the middle and outer regions of the combustor, the mixture strength suggested by Figure 15 is relatively weak. Consequently, associated with these areas would be a low laminar burning velocity, which would account for the sharp drop off in ignition performance highlighted in Figure 14; it is unclear why such a poor ignition performance was obtained at the position between the vaporiser and the outer wall of the combustor where the local mixture strength would appear to be beneficial to ignition.

After reviewing the experimental data, which included some limited velocity data, it became clear that the reason for the poor calculated fuel distribution was a poor prediction by the CFD of the primary jet interaction and subsequent mixing. The accuracy of a CFD prediction is related to the accuracy of its inlet boundary conditions. For the CFD contour plots shown in Figures 11 & 12, the inlet boundary conditions (e.g. port inflows and vaporiser inflow) were assumed to have a 'top hat' profile. Clearly, the difference between measured and calculated scalar distribution indicates that such an approach was too simplistic.

The availability of empirical fuel fraction and velocity data meant that a more realistic set of inlet boundary conditions for the model could be implemented. Shown in Figures 16 and 17 are revised fuel fraction and K distributions on a plane passing through the vaporiser inlet based on the experimental inlet boundary conditions. The introduction of the revised boundary conditions has resulted in a prediction of fuel fraction that is much closer that measured (Figure 16) and this is reflected in the distribution of K. Consequently, there is improved agreement between the location of the best recorded laser ignition performance, Figure 14, and that which one would inferred from Figure 17. However, there are still some inconsistencies, particularly in the region directly in front of the vaporiser, where the K value of about 1.0 would suggest a poorer ignition performance than that recorded experimentally. The distribution of K shown in Figure 17, appears insufficient for complete identification of all suitable ignition sites. This is important, as not all regions are necessary easily accessible to laser ignition. An example of this is the region between the vaporiser and the inner combustor wall. Although possibly offering the best performance, the optical access problems render this area difficult to use. The availability of an alternative site at the front of the vaporiser would be beneficial.

Currently, to achieve the accurate predictions in K necessary for identification of all suitable laser ignition sites, the empirical data on for fuel fraction and turbulent energy distributions have had to be used directly to calculate K. Shown in Figure 18 are the values of K calculated from the measured data. If laser ignition probabilities are inferred from this distribution, then the areas identified as offering good ignition performance are, generally, in good agreement with the recorded data in Figure 14.

The large variability in ignition performance highlighted in Figure 14 indicates that recorded ignition capability is sensitive to where the laser is focused within the combustor. Altering this location alters the local AFR and turbulence intensity experienced by the laser ignited flame kernel (as quantified by the value of the Karlovitz stretch factor), thus changing the probability of successful ignition. Conversely, changes in the local AFR and turbulence intensity at a fixed ignition site within the combustor may also alter ignition capability. As these parameters are likely to change with differing combustor inlet conditions (due to changes in the patternisation of the fuel spray, for example) the selected laser ignition site may have to be a compromise to ensure reliable ignition at other inlet conditions.

CONCLUSIONS

The possibility of utilising laser ignition to ignite reactive mixtures in a research gas turbine combustor at atmospheric pressure and 326 K has been demonstrated. In this preliminary study, an Nd:YAG laser was used to deliver an ignition energy of approximately 176 mJ to the combustor, which incorporated Perspex sidewalls for optical access. In comparison with the ignition performance of a conventional wall mounted SDI system, the laser ignition showed no additional benefit when it was located at approximately the same position as the SDI. However, when the laser ignition site was moved to a remote location at the head of the combustor, which was away from the combustor wall, the mass flow rate and AFR at which a ≥75% ignition probability could be achieved increased by approximately 33% when compared to the SDI. However, the observed improvement in ignition performance was shown to be closely related to the chosen remote laser ignition site; poor location of the site could result in a significant degradation of ignition performance when compared to the conventional SDI. Thus, a reliable means of identify suitable ignition sites is important.

A model based on a Karlovitz stretch factor, used in conjunction with a CFD flow field prediction, has been proposed to identify regions within the combustor that would prove beneficial if used in conjunction with laser ignition. Whilst the Karlovitz model was able to reproduce the experimentally observed tends in ignition probability, the model was found to be sensitive to the accuracy of the CFD prediction. Reliable Karlovitz predictions were only possible when experimentally measured fuel and turbulence intensity distributions were used.

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Laser Energy, mJ	Energy absorbed, mJ	% Absorbed
60	0	0
76	5	6.5
91	7	7.7
105	24	22.9
120	52	43.3
135	60	44.4
152	83	54.6
166	97	58.4
176	111	63.1

Table 1. Energy absorbed during laser ignition breakdown.

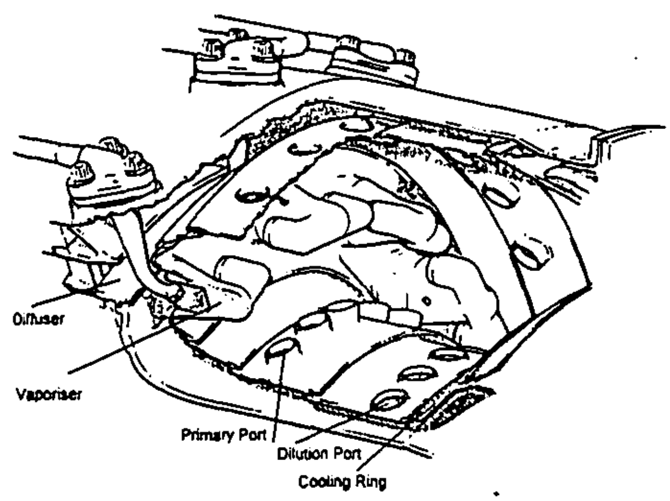

Figure 1. Pictorial view of research combustor geometry.

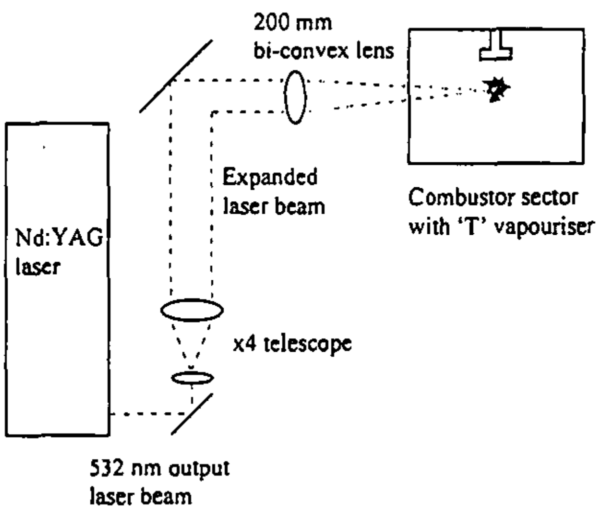

Figure 2. Laser ignition optical arrangement.

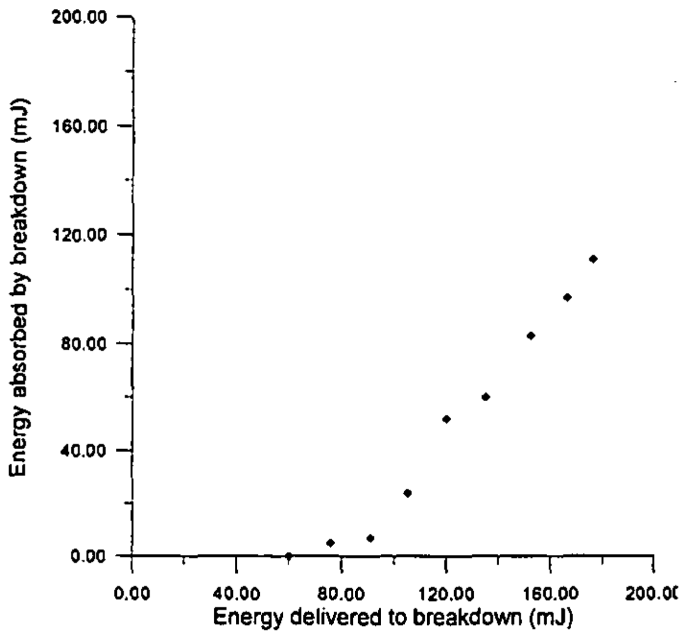

Figure 3. Variation in absorbed energy with delivered energy for a laser induced spark breakdown.

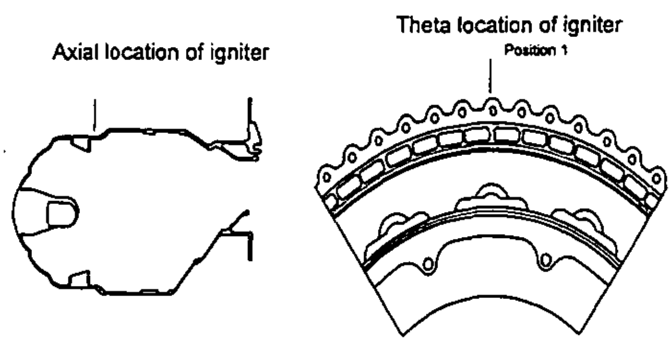

Figure 4. Surface discharge ignitor location in combustor

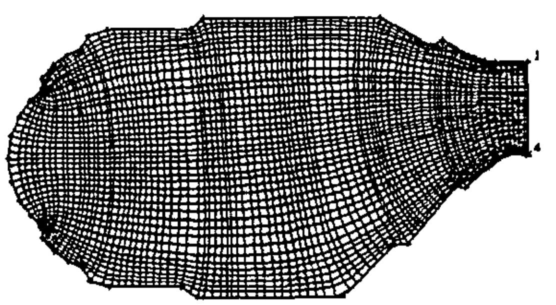

Figure 5. Combustor solution mesh in combustor plane.

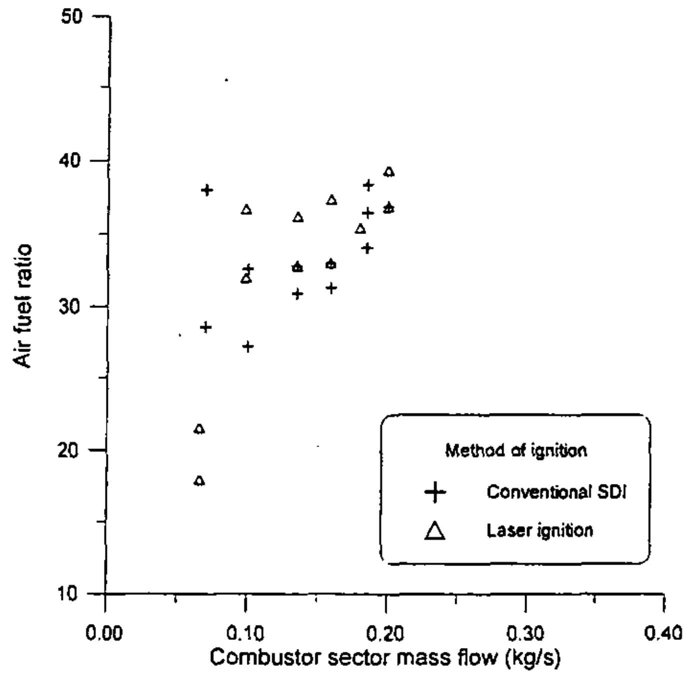

Figure 6. Comparison of ≥75% ignition probabilities for laser and SDI methods at the conventional SDI wall mounted location. Inlet pressure and temperature = 1.06 bar and 326 K, respectively; at an AFR of 40:1.

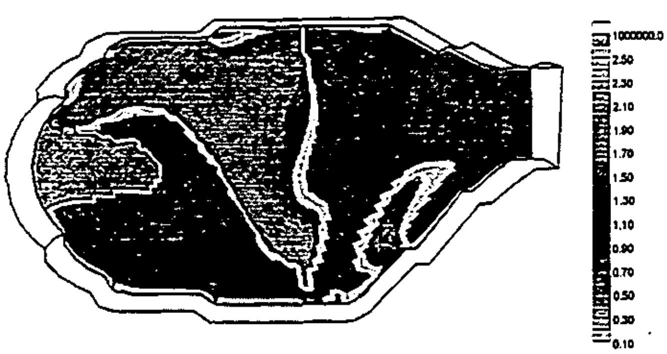

Figure 7. Contour plot of Karlovitz number distribution for inlet conditions of 0.21 kg/s at Inlet pressure and temperature = 1.06 bar and 326 K, respectively; at an AFR of 40:1.

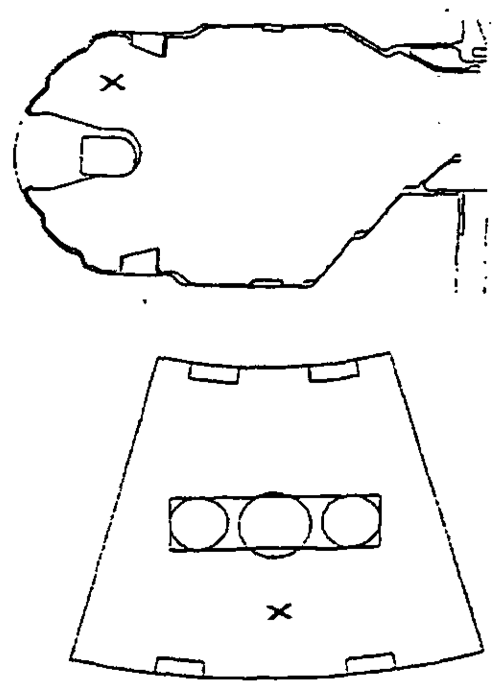

Figure 8. Remote Laser Ignition Site 1.

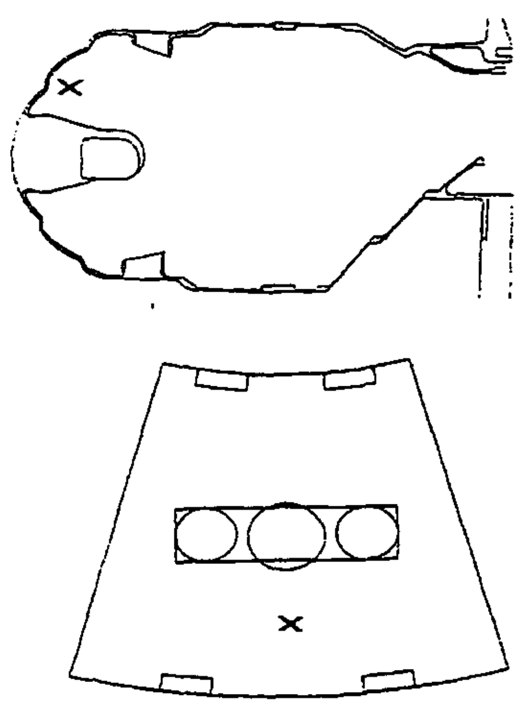

Figure 9 Remote Laser Ignition Site 2.

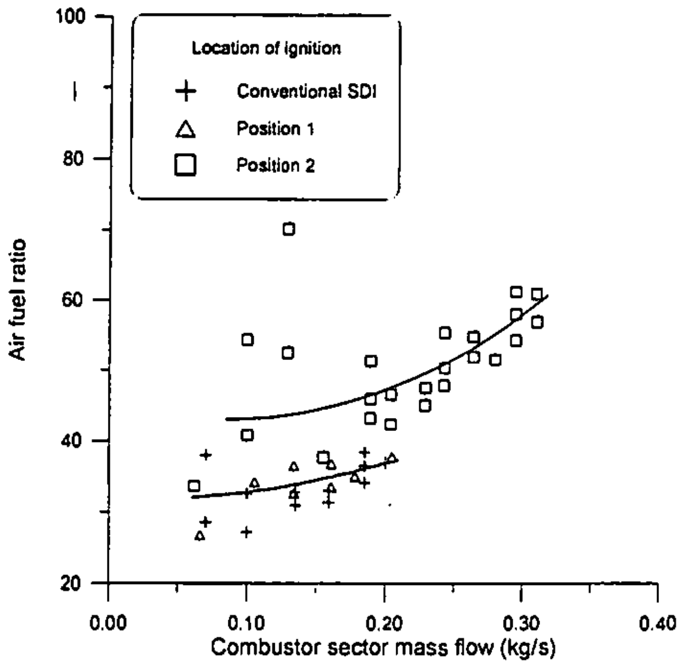

Figure 10. Comparison ≥75% ignition probability for laser ignition at Sites 1 and 2 and conventional SDI. Inlet pressure and temperature = 1.06 bar and 326 K, respectively; at an AFR of 40:1.

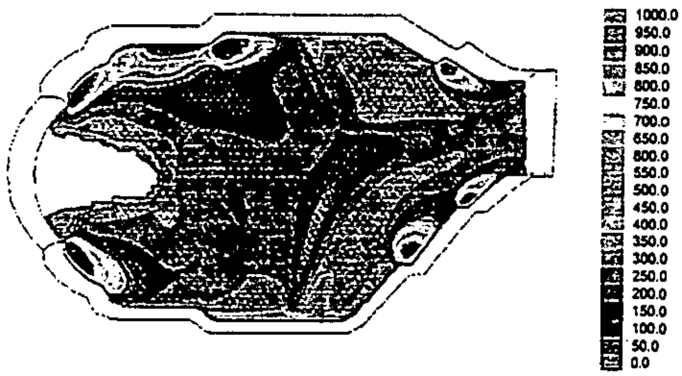

Figure 12. Predicted turbulent energy distribution from which Figure 7 derived.

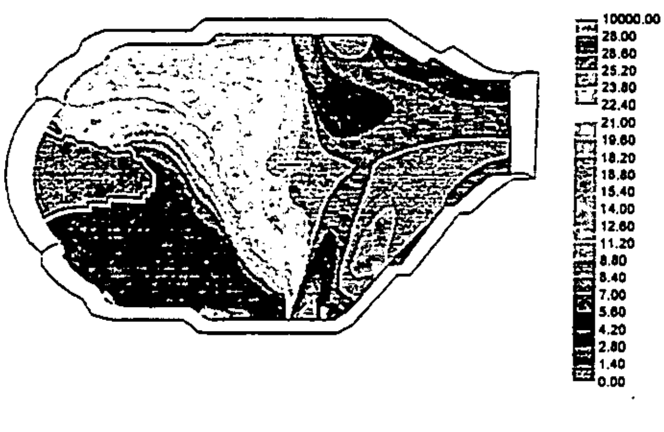

Figure 11. Predicted fuel scalar distribution from which Figure 7 derived.

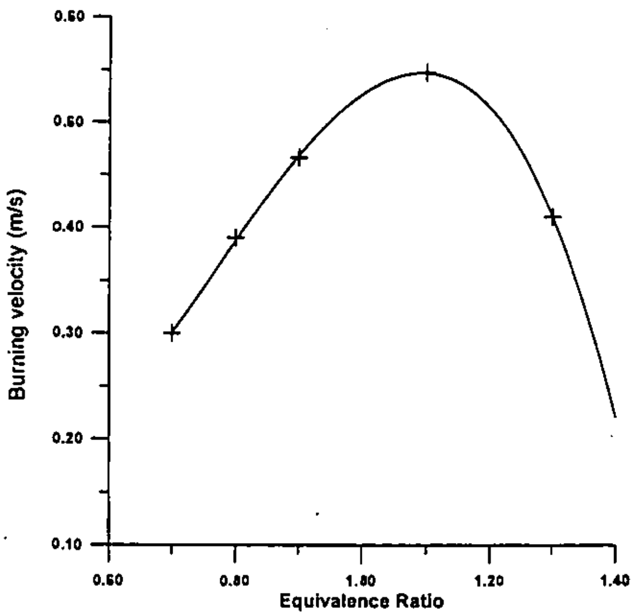

Figure 13. Variation of laminar burning velocity with equivalence ratio for a propane-air mixture at 1 atmosphere and 328 K. After Abdel-Gayed et al. [28].

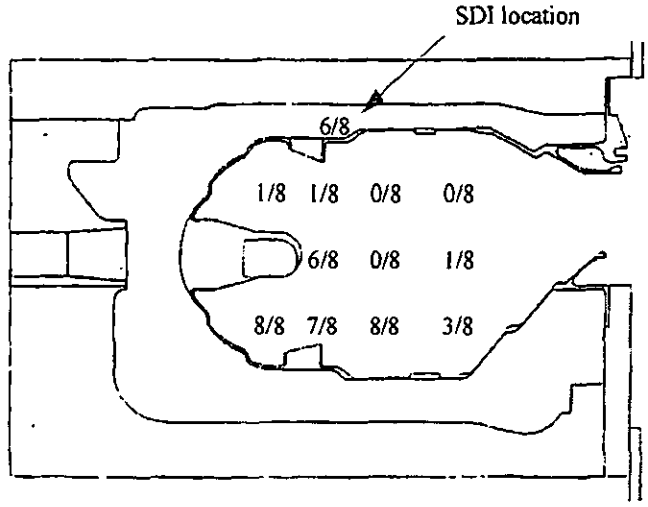

Figure 14. Laser ignition probability distribution on central plane passing through vaporiser inlet.

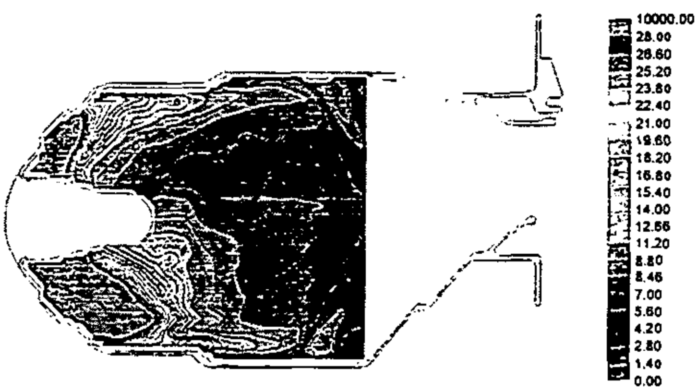

Figure 15. Measured 'fuel' scalar distribution for sectored research combustor.

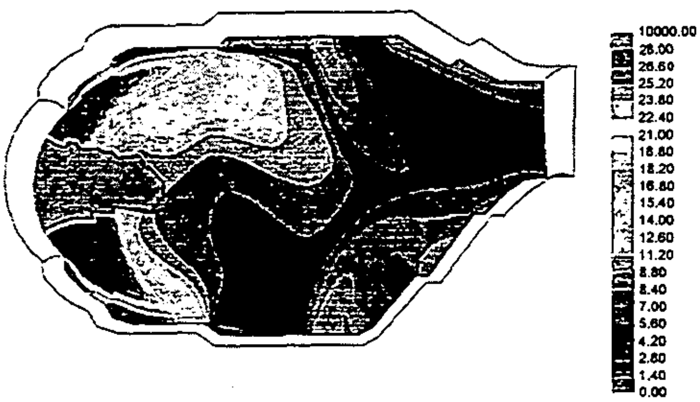

Figure 16. Revised CFD fuel scalar contour plot based on experimental inlet boundary conditions.

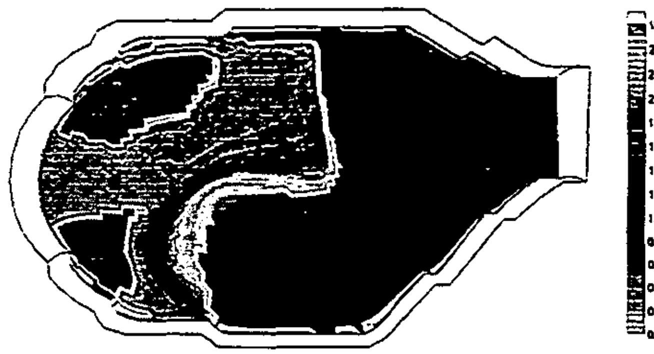

Figure 17. Revised Karlovitz number contour plot based on CFD solution using experimental inlet boundary conditions.

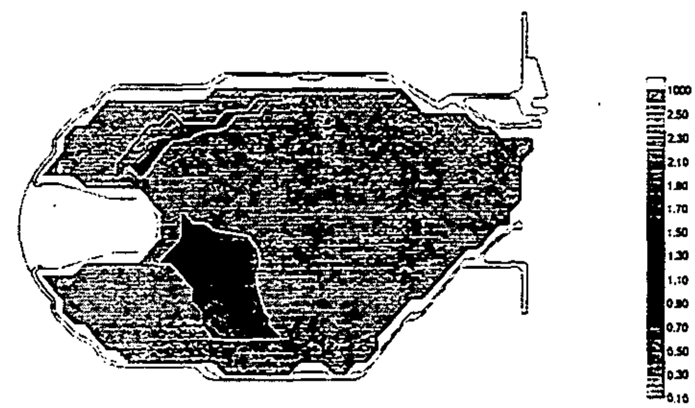

Figure 18. Contour plot of Karlovitz number derived using empirical fuel scalar and turbulent energy distributuions.