Rating of DI Diesel Combustion System Configuration by Mixing Indexes

P.Belardini, C.Bertoli, F.E.Corcione, N.Del Giacomo and G.Police

Istituto Motori CNR
Via Marconi 8
80125 Napoli
Italy

ABSTRACT

The influence of combustion system design on pollutant emissions of a D.I. T.C. light duty diesel engine was analyzed.
Combustion chamber with different shape were tested. Three-dimensional computations of air flow field and injection process were performed: thus capabilities offered by 3D simulations of in cylinder phenomena to engine designers are examined.
In order to obtain a quantitative tool from 3D calculations mixing and performance parameters are proposed and tested.
The proposed mixing index, defined as the ratio between air trapped in the fuel jets and total air in the combustion volume, is sensitive to engine design and operating conditions and allows a correct ranking of the different combustion system design.

INTRODUCTION

In a direct injection diesel engine, the air fuel mixing strongly influences the evolution of combustion and pollutants formation. A detailed analysis of inflow characteristics and air flow - fuel jets interactions can be performed using today available three-dimensional simulation codes.

In fact the status of development of multidimensional numerical calculations allows a reasonable picture of in cylinder phenomena at the end of ignition delay period.

For engine designers it is really important to assess the capabilities of this kind of calculations, in order to compare different configurations of the combustion system arrangement especially from the point of view of engine's pollutant emissions. An useful approach to this problem may be obtained by integrated use of multidimensional modeling and field experiments.

Therefore in the present work it has been analyzed the mixture formation process using different combustion chamber geometries in a four stroke D.I. T.C. diesel engine having total displacement of 2.51. Numerical and field experiments were carried out in order to formulate and test mixing parameters, sensitive to the combustion system design.

NUMERICAL MODEL

In this paper numerical calculations were performed by means of 3D KIVA code [1], modified at Istituto Motori in order to obtain better simulation of air - fuel jets interaction.

In particular a K-ϵ turbulence model was installed; in addition It has been implemented the capability to simulate multi-hole injectors and more realistic injection rate law. Moreover, as experimental investigations on modern high speed engines evidenced in many cases the fuel jet impingement on combustion chamber's wall, the injection model was improved as reported in [2], [3].

Finally, in order to process non axisymmetric combustion chambers, it has been set up a preprocessor, that easily allows to generate a grid for these kinds of chambers.

COMBUSTION CHAMBERS

In order to understand how the calculations are sensitive to the change of combustion system design, combustion chambers shaped in many different ways were selected. In particular four axisymmetric combustion chambers and three four-lobes square chambers were chosen.

In Fig. 1 the axisymmetric ones are shown. Two equivalent aspect ratios (EAR) were selected: actually 2.8 and 3.5. The 2.8 EAR combustion chambers, denoted by SR and SQ, have about the same values of flank angle and squish area, but the SQ one has a flat bottom in the bowl. The combustion chambers denoted by ST and LN have both an EAR of 3.5, but they differ for the

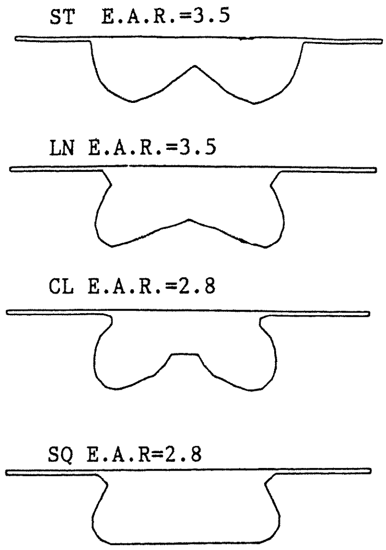

Fig. 1 Axisymmetric combustion chamber

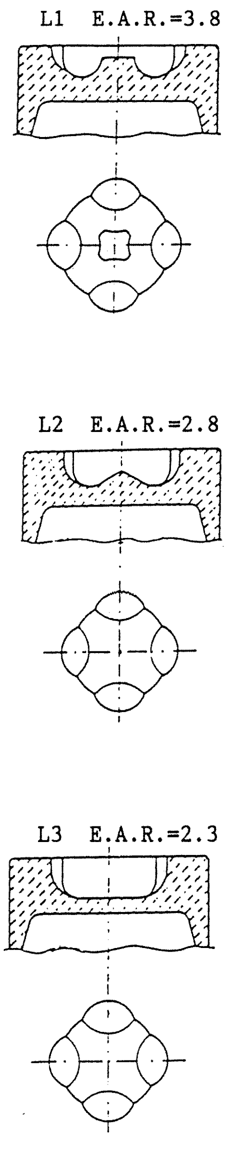

Fig.2 Four lobes chambers

squish area and flank angle value.

With reference to the squared combustion chambers, this kind of geometry was chosen because it seems to be of promise in order to obtain more favourable trade off NOx particulate [4], [5], [6]. The fluid-dynamic characteristics of these chambers were previously investigated by L.D.A. measurements as reported in [9].

The three selected squared combustion chambers are reported in Fig. 2. They differ for the EAR values, actually 3.8, 2.8 and 2.3, and for the central pip shape: the chamber denoted as L3 has a flat bottom in the bowl.

EXPERIMENTAL PLANE

Each selected combustion chamber was tested on the D.I. T.C. engine, whose characteristics are reported in Table 1. Tests were carried out at peak torque and rated speed, at full load conditions, but varying dynamic injection timing. Obviously the same test points were used for numerical calculations.

- D.I. T.C. FOUR CYLINDER DIESEL ENGINE	
- STROKE:	90 mm
- BORE:	93 mm
- INJECTOR:	4-0.28-144
- RATED POWER AND SPEED:	67Kw-3800 rpm

Table 1 : Engine characteristics

The engine was equipped with transducers to detect indicated pressure, needle lift and injection pressure laws.

RESULTS

<u>Axisymmetric Combustion Chambers</u>

The emission behaviour of the four tested axisymmetric combustion chambers is synthesized in Figs. 3, 4: the diagrams are referred to full load conditions, at rated speed and as well as at peak torque speed, varying dynamic injection timing.

At 3800 rpm SQ combustion chamber gives more favourable NOx particulate trade-off with respect to the standard one, while the CL chamber gives a worsening in performance. The LN combustion chamber exhibits good performances at widely retarded timings, while at standard injection timing its behaviour is similar to the ST chambers'.

Viceversa at 2200 rpm the best performances are given by the ST chamber, while each other shows a worsening in emissions behaviour.

It is really difficult to explain these trends with the simple concept of equivalent aspect ratio. If the only EAR value should control the optimum swirl conditions for a given design of injection system and inlet duct, the combustion

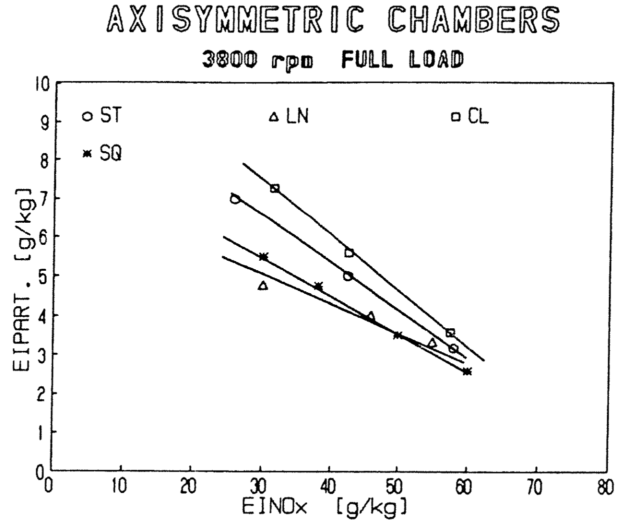

Fig.3 NOx-particulate trade off 3800 rpm full load

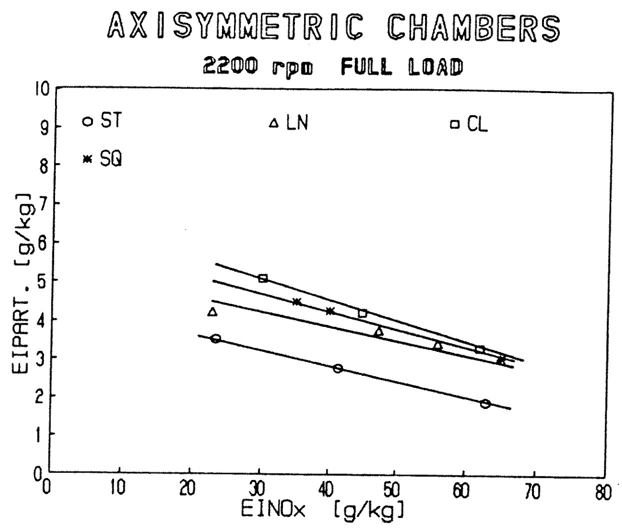

Fig.4 NOx-particulate trade off 2200 rpm full load

chambers with reduced EAR ratios should give better results at lower rpm. In addition, at same rpm, the reentrant bowl LN chamber should give better control of fuel impingement, if jets reached the combustion chamber wall.

However in the modern high speed D.I. engines up today in production, with the swirl assisted combustion systems the adoption of helical inlet port is quite general. Tests carried out on steady state test rig showed that for the majority of these ducts the swirl number falls in the range 2.5-3.5. With a given injection apparatus, usually the combustion chamber design is chosen to obtain smoke limited emissions at low engine speed and full load conditions. On the other hand, in these conditions, the engine operates nearly always in over swirl conditions at higher rpm.

It can be noted that the same definition of over swirl and under swirl condition is not well assessed. In a simple conceptual model it can be argued that the over swirl condition can be achieved in the combustion chamber whereas, due to high values of air motion, different jets interfere in fuel vapour transport.

In similar way the under swirl condition can be referred to the lack of oxygen transport in the jet due to the insufficient exchange of momentum between air and fuel jets. However full explanation of these effects must take into account other parameters such as the jet's real path before wall impingement, the amount of the impingement itself and the interaction between swirl and squish motions.

In addition experiences with high speed cinematography during the combustion process suggest a different physical mechanism to define over swirl condition; it is well known that in high speed engines, in order to obtain better degree of air utilization, the spray cone angle is usually chosen in the range 145-160 degrees. This choice is supported by the opinion that the utilization of the air included in dead volume can improve combustion in the beginning stage.

Y.Aoyagi [8] found that, in case of overswirl condition, the swirl strength can cause that the flame exists only in the bowl space: due to strong swirl, the flame in the bowl continues to rotate and, in absence of mixing with outer air, the air entrainment becomes poor.
It can be noted that this phenomenon can be made more conspicuous by the well known phenomenon of the spin-down at the end of compression stroke. In fact on dependence of squish area value and swirl number evolution during compression stroke, the interaction between squish and swirl motions can compress the air charge in the bottom of the bowl.

In conclusion, only fully three-dimensional computer simulation can improve the understanding of the complex interaction between the just described phenomena.

The numerical simulations were performed starting calculations at 90 CA BTDC; the initial conditions were obtained from LDA measurements carried out on an optically accessible engine with a bore to stroke ratio close to the test engine one [9], [10].

The injection parameters were chosen on the basis of experimental measurements of injection rate, dynamic injection timing, duration and ignition delay values. For each case the start of injection was selected at 10 C.A. before TDC and calculations were stopped at the end of ignition delay period.

If we analyze the air flow field at 3800 rpm, it can be noted strong increase in tangential swirl velocity near the wall for all reentrant chambers, but lower values in the center of the bowl with respect to the ST one (Fig.5).

a) ST CHAMBER

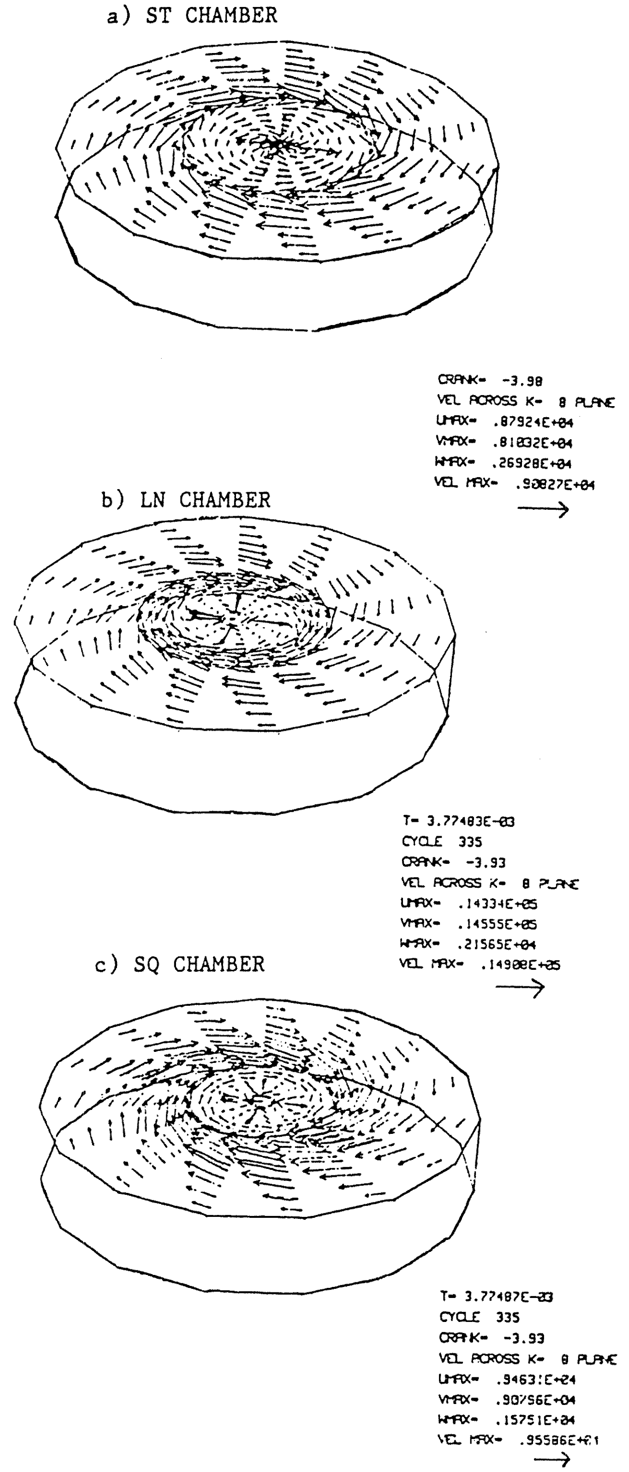

Fig.5 Examples of air velocity distribution for ST and reentrant chambers; 3800 rpm 4° C.A. B.T.D.C.

The presence of central pip in CL chamber promotes higher values of swirl components with respect to the SQ chamber even if EAR ratio, squish area and flank angle values are quite the same.

The air flow field distribution in the center of the bowl of reentrant chambers and the reduced distance between tip of injector and wall allows the fuels jets to reach the wall itself, while for the ST chamber this condition is not achieved (Fig.6). Probably this effect improves the mixing levels in good agreement with better performances showed by LN and SQ chambers.

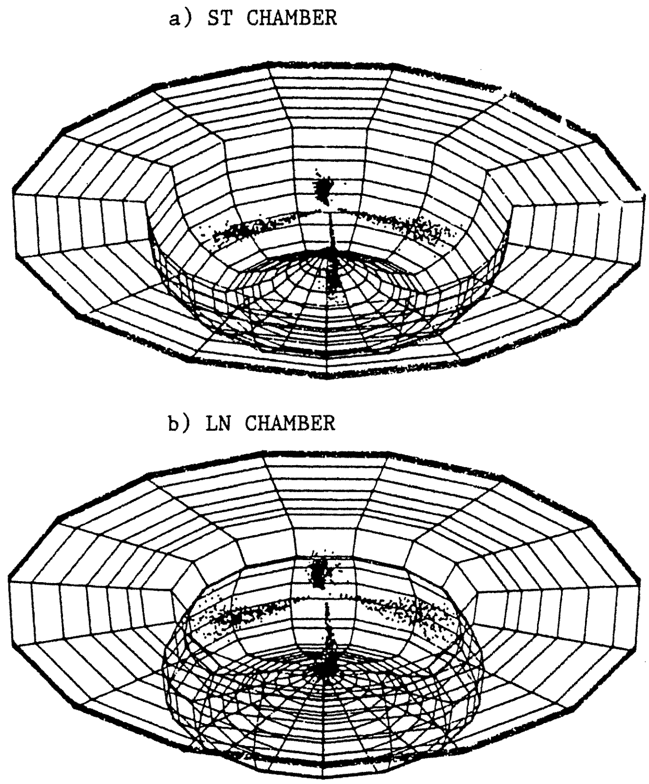

Fig.6 Examples of jets penetration at the end of ignition delay period; 3800 rpm, full load

The worsening in performances with the adoption of CL chamber is probably due to the too strong increase of swirl component that can cause the overswirl condition.

At 2200 rpm for every combustion chamber a strong interaction between jets and bowl wall can be detected (Fig.7). The air velocity increase in the periphery of the compact reentrant bowl cannot overcome the unsatisfactory effects of the too large amount of fuel impingement.

For example, in Fig. 8 the fuel/air ratio distribution is reported for ST and SQ chambers in an azimuthal plane containing the tip of the jets at the end of ignition delay period. A larger amount of fuel is clearly detected for the reentrant chamber.

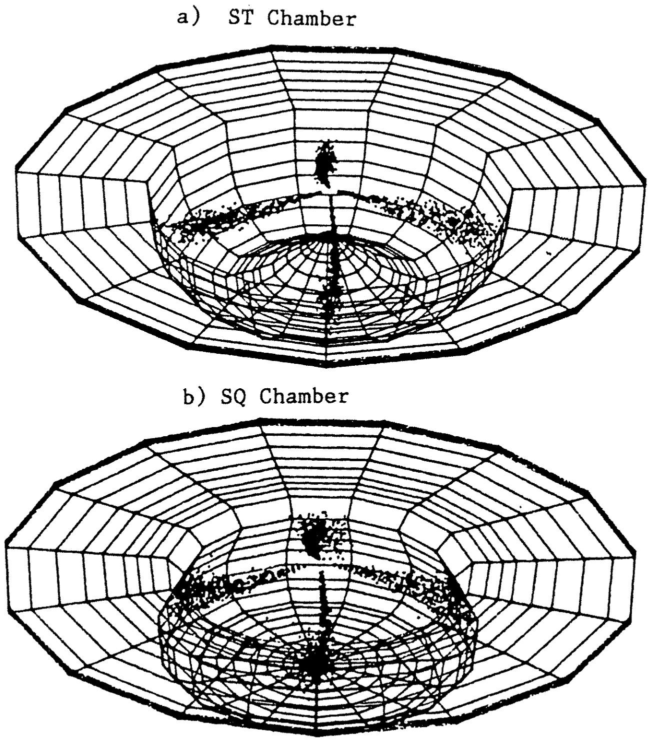

Fig.7 Examples of jets penetration at the end of ignition delay period; 2200 rpm, full load

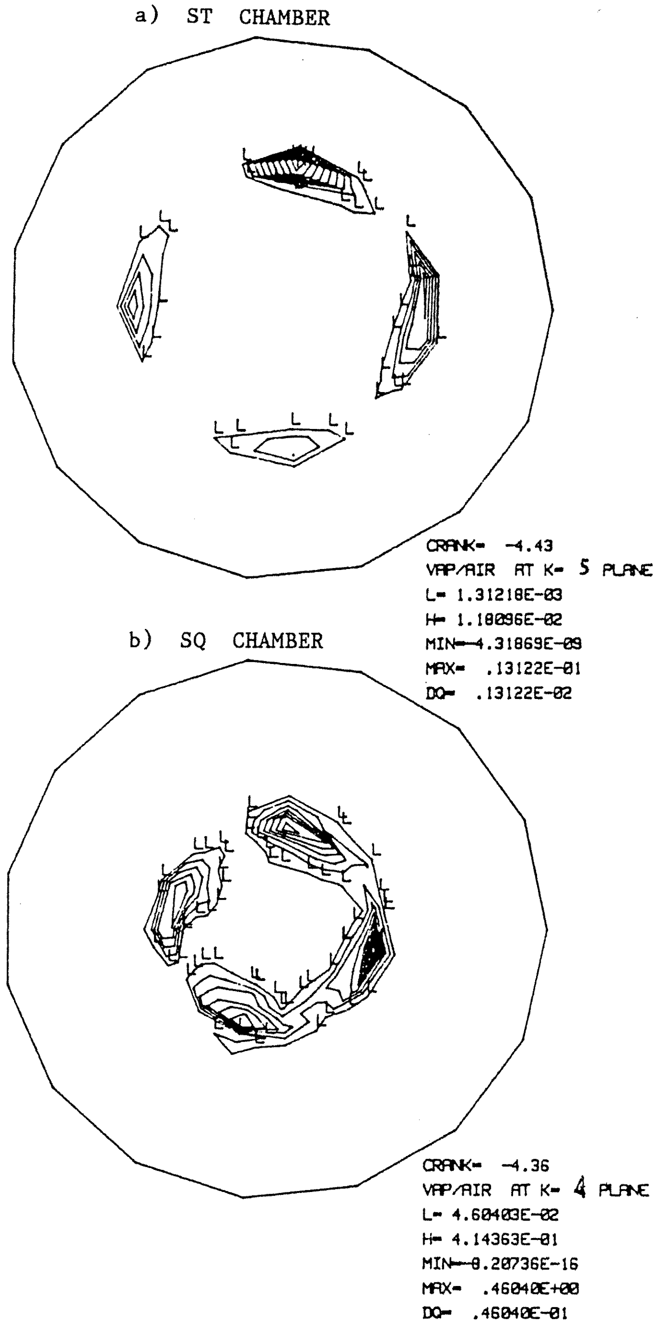

Fig.8 Fuel vapour/air contours for a) standard chamber and b) reentrant SQ chamber; 2200 rpm, full load

<u>Non Axisymmetric Combustion Chambers</u>

In previous papers [4],[6] the experiences carried out in Istituto Motori in the field of squared combustion chambers development were described. These experiences showed that the combustion system is very sensitive to the geometric features (aspect ratio, radius, etc.). In addition some recent tests have assessed that increase in injection rate can improve NOx and particulate at certain engine speeds [7].

The full load NOx particulate trade off of the three tested combustion chambers is reported in Figs. 9, 10 at 3800 and 2200 rpm respectively.

In comparison with ST axisymmetric chamber, all the microturbulence chambers give better results at higher rpm. Only for L2 chamber tests were carried out with injector operating pressure raised up to 250 bar. In these conditions a significant improvement in NOx particulate emissions trade off was found. At low engine speed just L2 chamber with higher injection pressure and L3 one give acceptable results; but in any case performances seem to be worse than for ST chamber. As pointed out in [6],[7] the most interesting characteristic of squared chambers is that at the end of compression stroke the turbulence intensity increase in lobes area, while mean swirl velocity is lowered.

This effect is clearly shown in Fig. 11, where air flow field for L2 and ST combustion chambers are compared 10 C.A. before TDC. The plots are referred to an azimuthal plane inside the combustion chamber.

In the case of squared combustion chamber, the concept of equivalent aspect ratio is very unsuccessful to understand the performance behaviour. In fact the energy transfer from mean motion to microscale motion in the final zone of fuel jet path strongly influences the mixing process. This effect can explain the experimental results at 3800 rpm. Even if the combustion chambers have different value of EAR and maximum swirl component, in any case very high values of turbulent kinetic energy in the lobes were computed (Fig.12). As the fuel jet for each chamber does not impinge on the wall, the improved performances with respect to the ST chamber can be only due to the previous described effect (Fig.13).

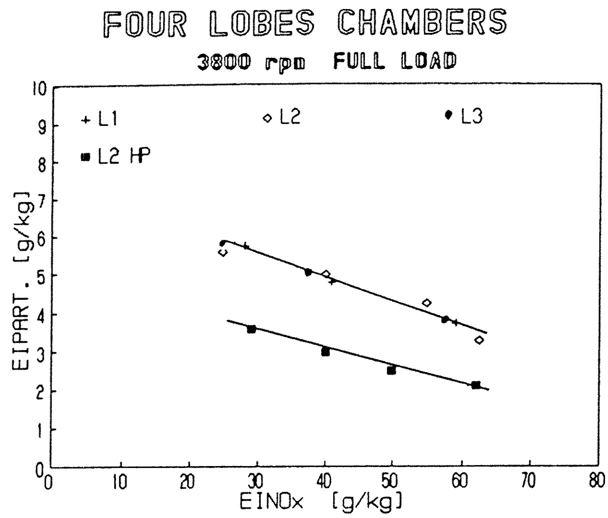

Fig.9 NO_x-particulate trade-off 3800 rpm, full load (L2 HP : chamber L2 high injection pressure)

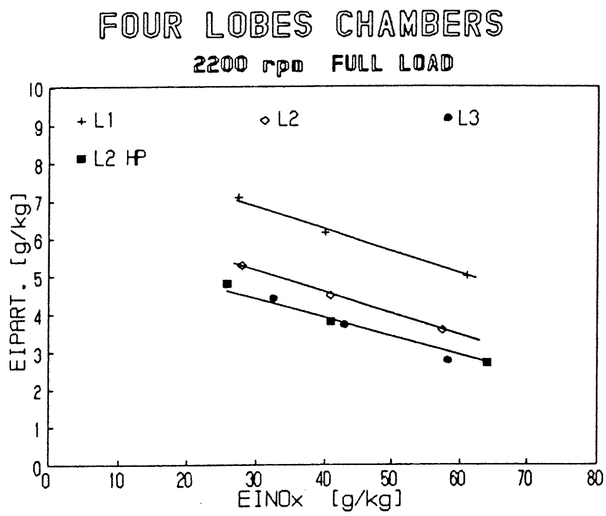

Fig.10 NO_x-particulate trade-off 2200 rpm, full load (L2 HP : chamber L2 high injection pressure)

The rise in injection pressure allows that the fuel jet reaches near the combustion chamber wall (Fig.14). Probably in this case the percent of fuel that impinges on the wall is quite the optimum.

At low engine speeds the strong reduction of mean swirl level is not offset by the increase of turbulence in lobes area and the engine works in under-swirl conditions.

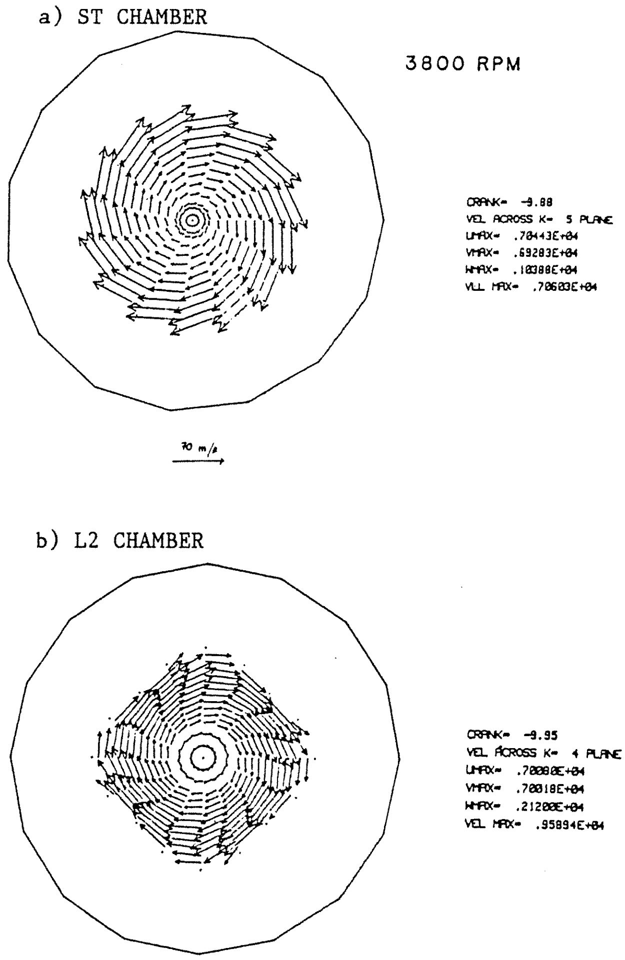

Fig.11 Air velocity distribution in the a) ST chamber and b) L2 chamber 3800 rpm, 10° C.A. B.T.D.C.

MIXING CORRELATIONS

In previous sections 3D calculations were employed in order to explain some experimental results regarding combustion systems having different design. However it is evident the lack of quantitative information from qualitative analysis of 3D calculations stopped at the end of ignition delay period. From this point of view we can affirm that the goal to provide engine designer with an useful tool by means of 3D simulation to develop engines with optimized air motion has not been realized up today.

In fact without field experiments the only simulation results are very difficult to be read and interpreted because of the large amount of data involved. Therefore the availability of integral indexes, sensitive to engine geometry and well related to engine performances, can contribute to a friendly use of multidimensional modeling.

In previous work [7] an index was proposed, that took into account the air entrainment in the jets: in particular it was the ratio between air trapped in the jets and total air in the

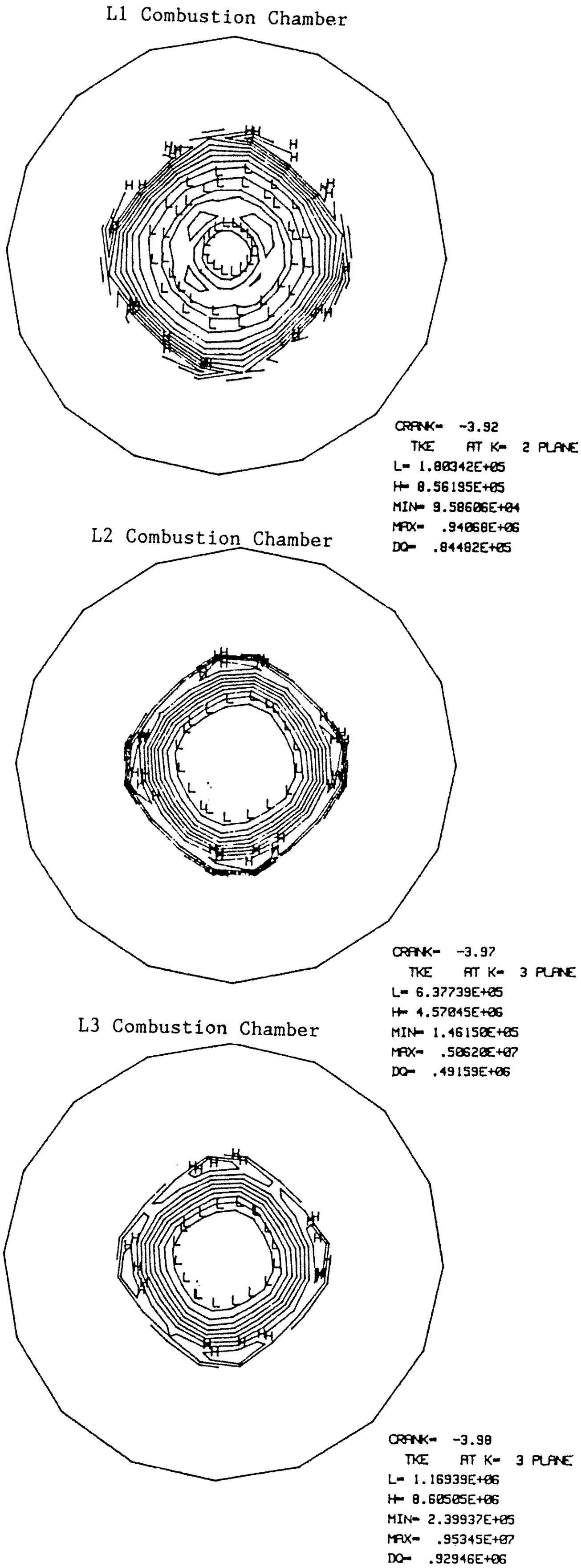

Fig.12 Turbulent kinetic energy distribution in four lobes chamber; 3800 rpm, 4° C.A. B.T.D.C.

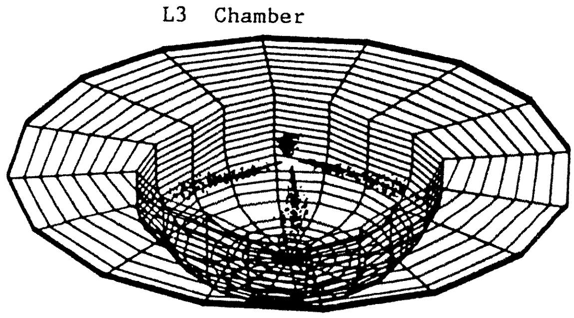

Fig.13 Jets penetration at the end of ignition delay period; 3800 rpm, full load

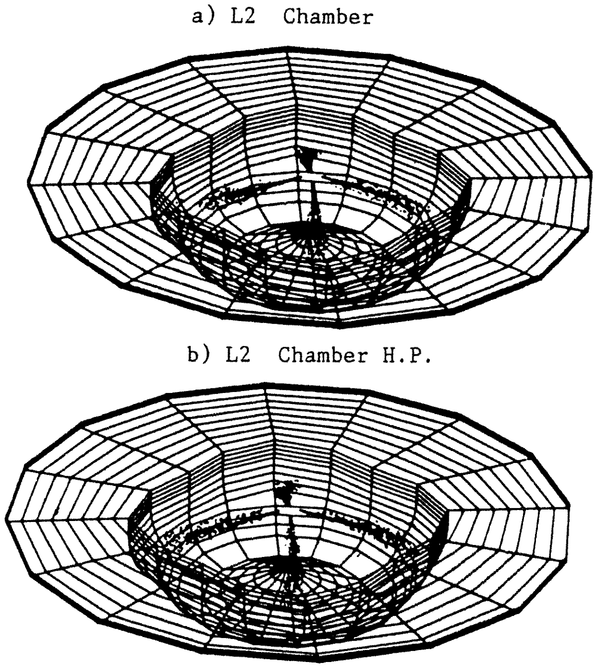

Fig.14 Jets penetration at the end of ignition delay period;
a) L2 standard injection pressure
b) L2 high injection pressure (H.P.)
3800 rpm, full load

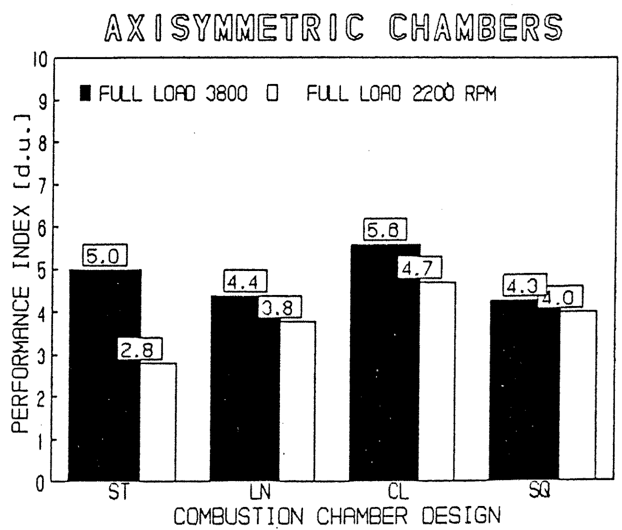

Fig.15 Performance index of axisymmetric combustion chambers

combustion volume. This index was tested with different engine configurations and it seemed to be insensitive to changes in injection law, probably because of limitations of the injection model in the employed KIVA code release.

In the present work the injection model has been improved by simulation of spray/wall interactions and capability to incorporate an experimentally fitted injection law. Moreover the performance analysis of the proposed mixing indexes has been extended to a larger number of combustion chambers and operating conditions.

In order to rank experimentally the combustion system configurations unambiguously, it is very useful to define as performance index the area under NOx particulate trade off. In the bar graphs of Figs. 15, 16 the trade off areas for axisymmetric chambers as well for the four lobes ones are reported. Clearly low values of this area indicate a favourable composite emission behaviour.

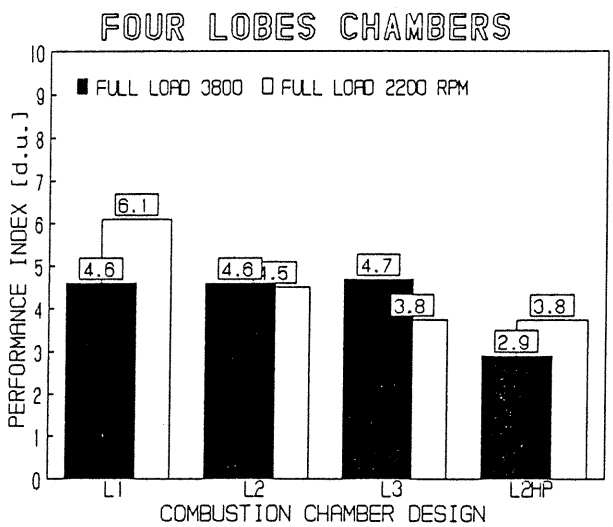

Fig.16 Performance index of four lobes combustion chambers

In Fig. 17 the just defined performance index is reported versus mixing indexes for each tested combustion chamber, at 3800 rpm. The results obtained are encouraging. In fact at 3800 rpm the mixing index shows good correlation with performance index: combustion chambers that have practically the same trade off, like ST, L1, L2, L3, are represented by a unique point. In addition the index is also sensitive to the rise in injection pressure, as shown by L2Hp test performed with a four lobes type L2 chamber.

It is interesting to note that at 2200 rpm the mixing parameter takes into account the reverse behaviour of same combustion chamber design. In fact the ST chamber, that shows the more favourable behaviour, is ranked by the highest mixing parameter value (Fig.18).

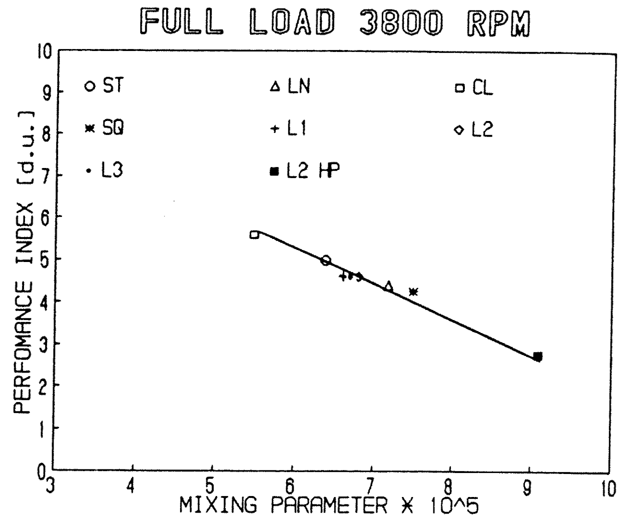

Fig.17 Mixing parameter vs performance index; 3800 rpm, full load

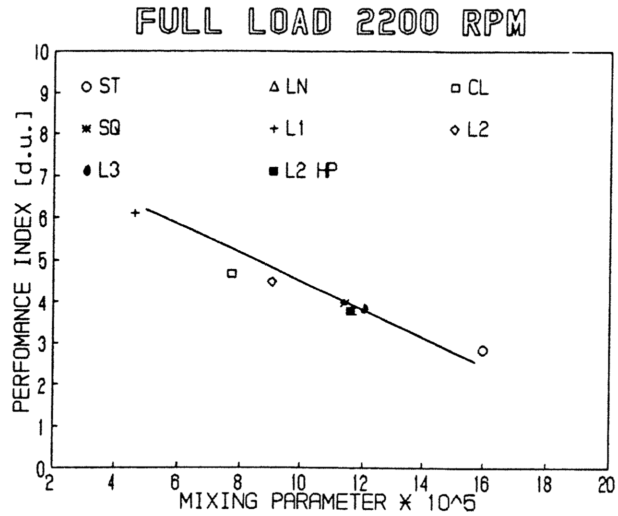

Fig.18 Mixing parameter vs performance index; 2200 rpm, full load

CONCLUSIONS

Combustion chambers having different design have been compared using both field experiments and 3D calculations.

The only numerical analysis of fluid-dynamic behaviour and air fuel mixing does not allow unambiguous explanation of experimental trends, even if it gives a large amount of information on process evolution.

The introduction of a mixing index from 3D calculations, sensitive to engine geometry and operating conditions, seems to be possible.

The ratio between air trapped in fuel jets and total air in the combustion volume is well related with emission behaviour of different combustion systems. Thus the proposed index can be an useful tool for engine designer to obtain relatively easy quantitative information by 3D numerical simulation stopped at the end of ignition delay period.

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