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MODELLING OF GAS ENTRAINMENT INTO A PILOT SPRAY IN A COMBUSTION BOMB

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ABSTRACT

Dual fuel combustion provides a convenient method of using natural gas in large, compression ignition engines. In order to study the complex combustion problems, a dual fuel combustion bomb has been designed and developed at the University of N.S.W. Different combustion modes have been identified, these being local and entrainment burning in the spray zone and flame propagation in the remainder of the mixture. The FLUENT code is being adopted in order to study the former in a three dimensional configuration. The time history of the entrainment and mixing processes are initially being studied during and following the transient injection period by use of continuous phase fluids. This has provided both useful information on these phenomena and on the appropriate method for further development.

INTRODUCTION

Natural gas is currently a prime contender as the most likely alternative fuel source during the early decades of the next century. However, because it consists predominantly of methane with a very low cetane number, it cannot be used directly in a compression ignition engine. One solution is the use of the dual fuel system whereby a premixed gas/air charge is ignited by a pilot distillate spray. This combustion process is complex because, in addition to the normal considerations of liquid fuel evaporation, mixing, ignition delay and combustion, the gas burning process may be characterised by a number of possible modes.

A number of studies (for example, Elliott and Davis, 1951; Felt and Steel, 1962; Karim, 1980; Karim, 1983), of dual fuel combustion exist which have been carried out on converted engines with the attendent problems of a large number of variables to be controlled and their effects understood. Currently, in order to minimise this difficulty, the dual fuel combustion process is being studied at the University of New South Wales using a constant volume, dual fuel combustion bomb (Milton, 1991; Hu, 1992). Many tests have been carried out with the natural gas/air charge introduced at a high pressure to give a pre-combustion pressure in the bomb in the range 1.4 to 2.2 MPa and with equivalence ratios from 0.5 to 0.9. The quiescent mixture is first heated to a temperature a little below that for gas ignition which simulates the end-of-compression condition in the engine cylinder. The distillate is then introduced in small quantities as a single shot spray through a standard 4 hole diesel injector raising the overall equivalence ratio slightly. Because both the ignition delay and minimum ignition temperature for the distillate is substantially less than that for the natural gas, combustion is initiated in the former and progresses to the latter. The results are being analysed by use of phenomenological models developed at the University of New South Wales. However, these make assumptions in relation to the burning modes and do not give a three-dimensional picture of the phenomenon in terms of pressure, temperature and species and an additional assessment is therefore required. A proprietary combustion code, FLUENT is currently being adapted for this purpose and its use is the subject of the present paper.

DUAL FUEL COMBUSTION

The combustion process in dual fuel engines may take several forms which may exist simultaneously or consecutively. These are:

i. **Local burning within the spray.** Here some of the natural gas/air mixture is trapped within the spray zone during the injection process. The combustion commences in the vaporised distillate and the gas already within the spray region is ignited by direct contact following the normal ignition delay period which, from the experimental evidence available,[Karim, 1967; Nielsen, Qvale and Sorensen, 1987; Milton, 1988], is itself modified by the gas, generally being lengthened. For this mode of burning to have a major effect, the spray region needs to have both a high penetration and a wide angle and these factors are not achieved simultaneously in diesel injectors.

ii **Entrainment burning.** The surrounding gaseous mixture is always entrained to some extent into a spray and this provides the oxygen for much of the combustion which occurs in the normal diesel spray process. For dual fuel combustion, the process is likely to be akin to that which occurs when a steady, gas jet impinges into a hot gas/air mixture. In the present case, the situation is at best quasi-steady and will exist only for the duration of the jet flow. During this time, the jet changes characteristics as it penetrates progressively through the mixture. With dual fuel combustion, if substantial quantities of gas mixture are entrained into the spray, this could provide a major contribution to the gas oxidation.

iii. **Flame propagation.** Once ignited, the burning gas acts like a point source ignition (for example, a spark) although it may be rather larger in extent and is likely to contain substantially more energy. It can therefore be a more reliable ignition source than a spark under marginal conditions such as those of very lean mixtures. Some flame quenching is possible particularly at the more remote walls when the mixture is very lean. Other problems of a similar nature to spark ignition engine combustion are the possibility of knock caused by end-gas autoignition.

All the above combustion processes require individual attention. In the current research, the aim is to examine the extent of the spray zone and mixing region for estimation of both the local and the entrainment burning.

THE FLUENT CODE

FLUENT is a finite volume, fluid-flow modelling software package specifically developed for chemical, aeronautical and mechanical applications. Built-in three-dimensional colour graphics allow the display of any calculated variable in terms of velocity vectors, profiles, contours, colour rasters and streamlines. Of particular relevance to this project is its capability to model a dispersed second phase, such as droplets and particles. Lagrangian trajectory computations are performed for them as groups based on the computed continuous flow gas phase field. The effect of turbulence on the second phase trajectories is modelled by a built-in stochastic tracing capability which takes into account the local turbulence characteristics as the particle traverses the flow field. FLUENT is fully coupled and so accounts for the exchange of momentum, heat and mass transfer between the droplets (particles) and the continuous phase.

While FLUENT was not developed for closed systems, it may be adapted to them by use of very small inlet and outlet areas with very low mass flow rates through the system controlled by manipulation of the pressure boundary conditions. Explorations in this direction are underway related to the transient pressure rise. These require the addition of ignition delay and flame propagation models to the code before it can simulate the full dual fuel combustion bomb burning process. As the intent of the current research is to estimate the extent of the spray and mixing zones, these regions can be treated as a flow system during the duration of the spray and the code is suited to this purpose.

Fig. 1 shows the appropriate boundaries for the system under consideration, which has inherent symmetry as the injector is a central, four equally spaced hole type. The system modelled numerically is a one eighth section of the bomb obtained by placing an injector hole at one radial edge and calculating to the radius mid way to the next hole. Discontinuous phases such as particles or droplets can currently be modelled by FLUENT only as steady flow phenomena while transient calculations require continuous phases. Thus, distillate droplets injected into a quiescent methane/air mixture could be studied as a steady phenomenon. This capability was initially used in the current research to determine the ultimate penetration and confines of the spray and the peak pressure reached during combustion but were replaced by continuous phase, non-combusting fluids for examination of the injection and immediate post-injection mixing processes.

From the experiments, it is known that the single shot injection pump produces maximum line pressures of between 17.5 and 22.5 MPa for a duration of 2 to 4 ms. The quantity of fuel injected at each of these settings ranges from 11 to 21.4 mg. Photographs show that the spray has a typical included angle of less than 18^{0}. Using this data, the spray was modelled as having an axial and velocity of 1 m/s and a

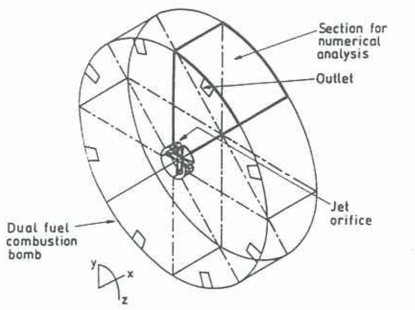


Fig. 1. Diagram of bomb and numerical boundaries

radial velocity of 10 m/s. These terms refer to the bomb, not the jet geometry, hence radial, axial and peripheral are respectively, x, y and z in the later diagrams. For the transient processes related to the injection, a gas jet impinging into a second, quiescent gas was used to simulate the spray phenomenon. The basic requirement of the simulation is that the gas jet has similar initial velocities to the distillate spray and a density ratio, gas jet to quiescent gas of around 50:1, similar to that of the distillate penetrating into methane/air. Hence, the gases chosen were argon at 300 K for the jet penetrating into helium at 1500 K for the quiescent mixture. Obviously, as these are inert gases, no combustion has been considered with this combination which is used only to examine the mixing process. While there will besome differences from the actual process due to the continuous rather than discrete nature of the spray and the effect of the other fluid properties, notably viscosity, it allows both an initial assessment to be undertaken and the appropriate simulation technique to be established.

NUMERICAL RESULTS

The 1500 K helium gas already in the bomb was given a typical experimental value for the bomb pressure of 2.2 MPa. This argon jet was allowed to flow for 4 ms (the maximimum for the experimental diesel injection) but the history of the mixing process was continuously recorded. After stopping the jet, the total computation was subsequently continued for over 90 ms to examine further mixing promoted by the jet over the full combuation process time period established experimentally. In practice, when combustion occurs, some modification or curtailment of the entrainment will take place but this was not considered here. FLUENT gives both alpha-numeric or graphical output as described previously, with representative examples of the latter being used here.

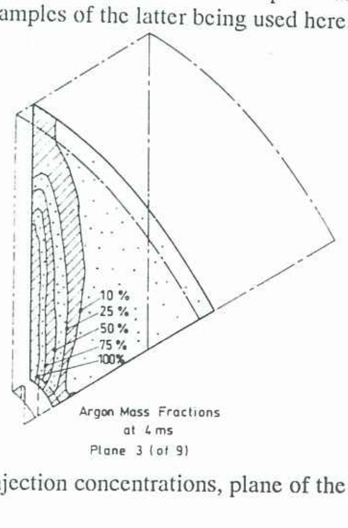


Fig. 2. End of injection concentrations, plane of the jet

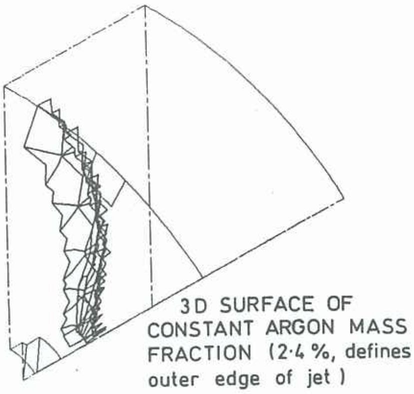


Fig. 3. Outer boundary of the mixing zone, 3D surface

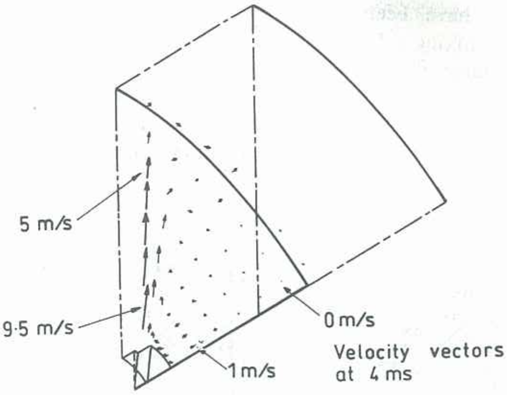


Fig 5. End of injection circulation, plane of the jet

Typical contours are shown on Fig. 2 for the time of 4 ms which is at the end of the injection phase. These are in the y,z plane (number 3) which extends directly out from the centre of the jet nozzle across the bomb. While the bomb radius, R is 54 mm and is so defined in the numerical model, it is convenient to express all dimensions as a fraction of R. Due to the position chosen for jet initiation, the maximum distance from the start of the jet to the wall is 0.87R. It can be seen that the jet extends as essentially undiluted argon in a narrow region of approximately 0.03R half width and 0.05R length surrounded by a progressively more dilute region where it diffuses into the helium. This is essentially the entrainment zone where the quiescent mixture is dragged into the jet. Contours delineating the edge of 100%, 75%, 50%, 25% and 10% argon concentration are shown. This last roughly defines the rich limit if the actual fuels are used to replace the continuous phase fluids and, since the ignition delay will be greater than 4 ms in most practical cases, it is likely that combustion will be initiated somewhere near this contour. Fig. 3 shows the outer edge of the mixing zone as a three dimensional surface defined arbitrarily as 2.4% argon, (this being a little below the lean limit for the actual fuels) and this location is confirmed by the density contours of Fig. 4. The vector velocities of Fig. 5 show the recirculation pattern starting to develop throughout almost the entire field with only a small quiescent region occupying less than 20% of the volume remaining in the outer corner furthest from the nozzle. Plots in planes further from the plane of the nozzle show similar but less developed trends. The maximum growth of the jet (in plane 3) and mixing region with time throughout the 4 ms injection period is shown as a series of argon concentration plots on Fig. 6.

Once the injection ceases, the jet immediately lifts off from the nozzle and progresses towards the outer wall while still growing in width. The region of 100% argon concentration becomes rapidly smaller although levels of around 75% persist over a reasonable volume to about 10 ms (measured after the start of injection). By 30 ms, these maximum concentrations have reduced to about 25%. A series of argon concentration profiles at 5, 10, 20 and 30 ms are shown on Fig. 7. The movement of the liquid from the original jet around the recirculation region is apparent. It can be seen from Fig. 8 that the recirculation velocities have increased in intensity and after 10 ms, the velocity in the previously stagnant corner (in plane 3) is now significant at about 0.2 to 0.5 m/s.

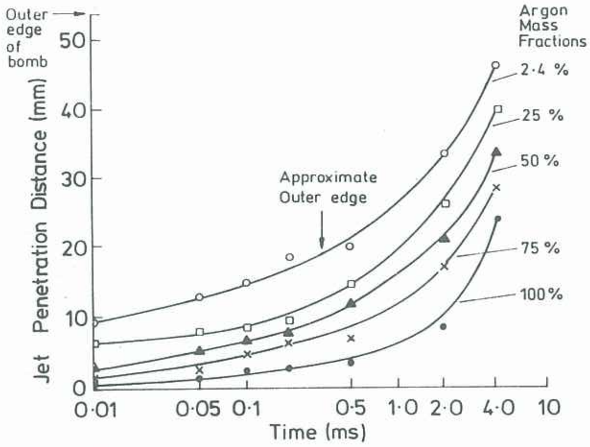


Fig. 6. Jet growth during injection, 0 to 4 ms

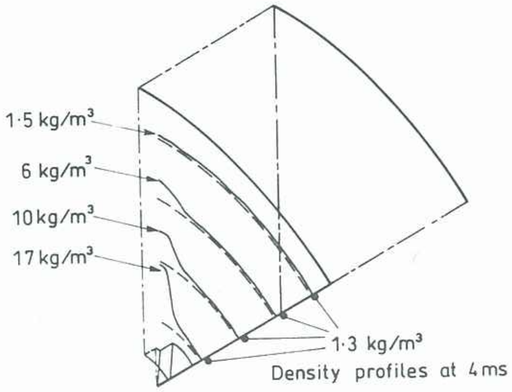
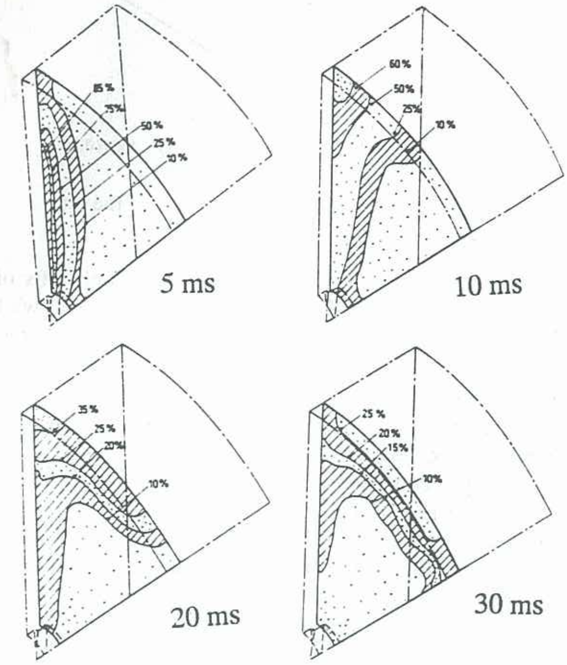


Fig. 4. End of injection density profiles, plane of the jet

DISCUSSION AND CONCLUSIONS

The results obtained so far indicate that the FLUENT code can be used to examine the flow in a constant volume, dual fuel combustion bomb. The continuous phase modelling used for the transient case has developed a technique which can be further refined at a later stage. At present only one sample case has been examined but some useful information about the entrainment and mixing modes has been obtained. In particular, they indicate that, for times in excess of about 20 ms, the entrainment process is such that almost all the field will have been drawn into the recirculation zone. However, mixing is by no means complete with perhaps 40% of the volume at this stage above 10% concentration and a further 25% approximately below 5%. Even when the calculation is continued to 130 ms, some non-uniformity still exists.. However, combustion initiation will occur at an



Argon mass fraction contours

Fig. 7. Concentration changes after cessation of injection

earlier time and will alter the above regions. Further studies which include this effect are required. Different initial conditions in the bomb and changes to the duration and quantity of the spray are factors which will cause different quantities of mixture to be entrained and both the spray and the initial bomb temperature will also affect the location and time of ignition. Gas/air equivalence ratio may not be as important a variable as, to some extent, the principle variations are based on spray volume and duration. However, they will change the ignition conditions.

A wide range of cases now needs to be studied parametrically. Combustible fuels and ignition models need to be included. Although not reported here, other initial studies show that the maximum bomb pressure can be predicted by the code with some accuracy. While this pressure currently rises too rapidly because there is no

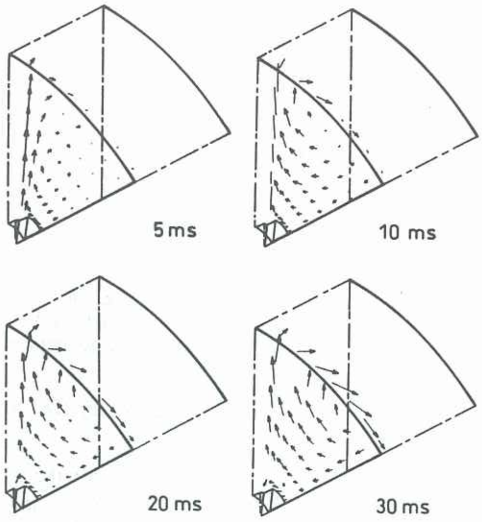


Fig. 8. Circulation increase after cessation of injection

ignition delay model in the code and a flame front is not predicted by it, these models can be incorporated at a later stage. It seems likely that the FLUENT code will then be able to be used for a full evaluation of this very complex combustion process.

REFERENCES

Elliott, M.A. and Davis, R.M., "Dual-Fuel Engine Combustion in Diesel Engines", Ind. Eng. Chem Ind. (Int.), 64, 2854, 1951.

Felt, A.E. and Steel, W.A., "Combustion Control in Dual-Fuel Engines", SAE Trans., 70, 644, 1962.

Hu, B., "Phenomenological Modelling of the Combustion Processes in Dual Fuel Diesel Engines using a Constant Volume Combustion Bomb", PhD Thesis, University of New South Wales, 1992.

Karim, G.A., "Knock in Dual-Fuel Engines", Proc. Inst. Mech. Engrs., Vol. 181, Pt. 1,No.20, pp.453-466, 1966-1967.

Karim, G.A., "A Review of Combustion Processes in the Dual Fuel Engine", Proc. Energy Combust. Sci., Vol. 6, pp. 277-285, 1980.

Karim, G.A. "The Dual Fuel Engine of the Compression Ignition Type - Prospects, Problems and Solutions - A Review", SAE 831073, 1983.

Milton, B.E., "Improving the Performance of Small Dual-Fuelled Engines", Paper 22, 1st NGV Int. Conf. and Exhib., Sydney, Aust., October 1988.

Milton, B.E., "Fundamental Problems in Minimising Pilot Distillate in Dual Fuel Engines", Progress Report, NERDDC, Australia, 1991

Nielsen, O.B. Qvale, B. and Sorenson, S., "Igntion Delay in the Dual Fuel Engine":, SAE 870589, 1987.